

Application No. 10/553,534
Reply to Office Action of September 29, 2008

Docket No.: 14113-00028-US

REMARKS

The applicant respectfully requests reconsideration in view of the amendments and the following remarks. The applicant has incorporated claim 7 into claim 1. The applicant has cancelled claims 11-13 and 15-18.

Claims 1-9 are rejected under 35 U.S.C. 103(a) as being unpatentable over Stern et al., US Patent No. 5,763,539 ("Stern") in view of Hontis et al., "Polymer 42 (20010 5793-5796" ("Hontis"), and as evidence by Taylor et al., "Substituted PPV's for Blue Light" ("Taylor"). Claims 11-13 and 15-17 are rejected under 35 U.S.C. 103(a) as being unpatentable over Stern as evidenced by Taylor. Claim 18 is rejected under 35 U.S.C. 103(a) as being unpatentable over Stern as evidence by Taylor as applied to claim 11, and further in view of Burroughes et al., US 2003/0124341 ("Burroughes"). The applicant respectfully traverses these rejections.

Rejection of Claims 1-9

Claims 1-9 are rejected under 35 U.S.C. 103(a) as being unpatentable over Stern in view of Hontis and as evidence by Taylor.

The Examiner indicated at page 3 of the Office action, that Stern does not teach the claimed mol%.

Stern teaches a process for preparing PPV derivatives using a different synthesis procedure, i.e. the synthesis from halomethylsulfinylmethylarylene (see page 3 of the Office Action and scheme 1 at col. 7 of Stern) and not Gilch polymerization (see the applicant's abstract). Again, as recognized by the Examiner at page 3 of the Office action, Stern does not teach that the monomer of formula (I) is used in an amount of 2-40 mol%. Stern discloses that the monomers for the polymerization reaction can generally be unsubstituted or they can be substituted at the halomethyl group or at the sulfinylmethyl group. However, Stern did not recognize that there is a technical effect associated with some of the disclosed monomers, in particular, when they are used in a content of 2-40 mol%. Furthermore, all examples of Stern use only monomers, which do not have an additional substituent on the halomethyl group.

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Therefore, even if monomers similar to the monomer of formula (I) of the pending application are disclosed by Stern, a person of ordinary skill in the art would have not be motivated to use these monomers for the solution of his technical problem, i.e. for a process for preparing PPVs with a controlled lower molecular weight and a high solubility.

It is correct that Stern teaches that reducing the molecular weight would be desired to prevent precipitation of the polymer and increase solubility. However, this is just the technical problem itself and not a solution for the technical problem and the applicant does not believe that Stern teaches how this could be achieved. Neither Stern, nor a combination of Stern with Hontis and/or Taylor would result in a polymer of lower molecular weight and increased solubility.

The Examiner accepts that all of the claimed effects are not positively stated by the references, however, the Examiner assumes that the claimed effects would be implicitly obtained as the references teach all the claimed ingredients and all process steps. The applicant agrees that a process that would be conducted with the ingredients disclosed in the references would lead to the desired polymers of lower molecular weight. However, the technical problem of the pending application is to find a process, with which it is possible to control the molecular weight during the synthesis of PPVs. Even though the combination of the references might result in polymers of lower molecular weight, the person skilled in the art would not have used a combination of the processes as disclosed in the prior art to solve his technical problem. None of the references suggest that the combination of the disclosed processes and ingredients could result in polymers of low molecular weight and high solubility at the same time. This is particularly true as Stern refers to a different polymerization reaction. Furthermore, it is not correct that Hontis suggests that the sulfonyl monomers and the halomethyl monomers are functionally equivalent, but Hontis states that the chemistry involved is only similar ("to synthesis this type of conjugated polymers various routes were developed including: the Wessling-Zimmerman[2], Gilch[3] and Sulfinyl [4,5] routes. These routes are based on similar chemistry...")

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However, Hontis further states, in the second full paragraph in the introduction at page 5793, that the complexity of the whole polymer synthesis makes the nature of the polymerization mechanism uncertain. As the polymer synthesis shows a complex mechanism, it cannot be concluded that the Gilch polymerization and the polymerization starting from sulfonyl monomers is equivalent and that the addition of monomers of formula (I) has the same effect on the reaction products for the different polymerization processes.

Furthermore, Taylor, disclose homopolymers of monomers of formula (I), which are described to be "largely insoluble" (see page 1121). It is correct that Taylor does not indicate the medium, in which the solubility has been determined, however, the statement "largely insoluble" suggests that the polymer is insoluble in a large variety of different solvents and that they did not find any solvents, in which the polymers showed a good solubility. This is already the case for the non-conjugated precursor polymer. It is generally known to a person skilled in the art that the conjugated PPVs have a considerably worse solubility compared to the corresponding non-conjugated precursor polymers. This general knowledge is for example supported by the publication by Wan et al., which is enclosed. On page 6569, Wan et al. disclose that the chloro containing precursor polymer is soluble while the conjugated PPV polymer is highly insoluble. This is also disclosed in a review publication by Kraft et al., which is also enclosed. On pages 404-405, Kraft et al. disclose that the PPV polymers are insoluble materials while the corresponding non-conjugated precursor polymers are solution processible and that this is valid for a whole range of PPV-related polymers.

Therefore, it can be concluded that the conjugated polymers disclosed by Taylor are even less soluble than the precursor polymers. These polymers are therefore not the solution for the technical problem of the present invention and the person skilled in the art would never use this teaching when trying to find a solution for his problem.

A statement that modifications of the prior art to meet the claimed invention would have been "obvious to one of ordinary skill in the art at the time the invention was made" because the references relied upon teach that all aspects of the claimed invention were individually known in the art is not sufficient to establish a *prima facie* case of obviousness without some objective

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reason to combine the teachings of the references. *Ex parte Levengood*, 28 USPQ2d 1300 (Bd. Pat. App. & Inter. 1993). See MPEP § 2143.01 IV. “[R]ejections on obviousness cannot be sustained by mere conclusory statements; instead, there must be some articulated reasoning with some rational underpinning to support the legal conclusion of obviousness.” *KSR International Co. v. Teleflex Inc.*, 82 USPQ2d 1385, 1396 (2007) quoting *In re Kahn*, 441 F.3d 977, 988 (Fed. Cir. 2006). Furthermore, the Examiner cannot selectively pick and choose from the disclosed parameters without proper motivation as to a particular selection. The mere fact that a reference may be modified to reflect features of the claimed invention does not make the modification, and hence the claimed invention, obvious unless the prior art suggested the desirability of such modification. *In re Mills*, 916 F.2d 680, 682, 16 USPQ2d 1430 (Fed. Cir. 1990); *In re Fritch*, 23 USPQ2d 1780 (Fed. Cir. 1992). Thus, it is impermissible to simply engage in a hindsight reconstruction of the claimed invention where the reference itself provides no teaching as to why the applicant’s combination would have been obvious. *In re Gorman*, 933 F.2d 982, 987, 18 USPQ2d 1885, 1888 (Fed. Cir. 1991).

In contrast, the polymers obtained according to the claimed process have a lower molecular weight and a high solubility at the same time. This is an unexpected and surprising result, which could not be predicted from the references. Therefore, claims 1 to 6 and 8 to 9 are not obvious over the combination of Stern, Hontis and Taylor. For the above reasons, this rejection should be withdrawn.

Rejection of Claims 11-13 and 15-17

Claims 11-13 and 15-17 are rejected under 35 U.S.C. 103(a) as being unpatentable over Stern as evidenced by Taylor. The applicant has cancelled these claims. For the above reasons, this rejection should be withdrawn.

Rejection of Claim 18

Claim 18 is rejected under 35 U.S.C. 103(a) as being unpatentable over Stern as evidence by Taylor as applied to claim 11, and further in view of Burroughes. The applicant has cancelled claim 18. For the above reasons, this rejection should be withdrawn.

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In view of the above amendment, applicant believes the pending application is in condition for allowance.

Applicant believes no fee is due with this response. However, if a fee is due, please charge our Deposit Account No. 03-2775, under Order No. 14113-00028-US from which the undersigned is authorized to draw.

Dated: December 29, 2008

Respectfully submitted,

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ENCLOSURE: Wan et al
Kraft et al

Electroluminescent Conjugated Polymers—Seeing Polymers in a New Light

Arno Kraft, Andrew C. Grimsdale, and Andrew B. Holmes*

A major recent development in the field of molecular electronics has been the discovery of electroluminescent conjugated polymers—that is, fluorescent polymers that emit light when excited by the flow of an electric current. These materials may now challenge the domination by inorganic materials of the commercial market in light-emitting diodes. Conjugated polymers are particularly versatile because their physical properties (color, emission efficiency) can be fine-tuned

by manipulation of their chemical structures. The development of polymer-based light-emitting devices has been accompanied by an increased understanding of the processes involved in device function and breakdown, and the systematic modification of the properties of the emissive polymers by synthetic design has become a vital component in the optimization of light-emitting devices. In this account we present an overview of the synthesis and properties of electroluminescent

polymers and demonstrate through examples the development of the field. There are many aspects of fundamental science to be studied in order to realize commercial applications of this serendipitous discovery. Opportunities for synthesis abound.

Keywords: conjugation · electrochemistry · luminescence · materials science · polymers

1. Introduction

The role of polymers in the electronics industry has been traditionally associated with insulating properties, whether these be for isolating metallic conductors or for use in photoresist technology. From that starting point it was the pioneering work of MacDiarmid, Heeger, and Shirakawa et al. that inspired chemists and physicists to consider the opportunity of using polymers as conductors. While the scientific community had started to accept the concept of conjugated polymers as semiconductors, no-one was prepared for the discovery of the plastic sandwich that would emit light when simply connected to a battery. The discovery in Cambridge of electroluminescence (EL), that is the emission of light when excited by flow of an electric current, in conjugated polymers^[1] has provided a new impetus to the development of

light-emitting devices (LEDs) for display and other purposes.^[2] Organic electroluminescent displays represent an alternative to the well-established display technologies based on cathode-ray tubes and liquid-crystal displays (LCDs), particularly with respect to large-area displays for which the existing methods are not well suited.

Inorganic electroluminescent materials have been known for many years, and LEDs based on these materials have been commercially available since the early 1960s. They have been widely used in a variety of applications. EL from molecular organic materials was discovered about the same time, but it was only in the mid-1980s that devices using fluorescent organic dyes showing brightnesses and operating voltages suitable for commercial applications were developed by Tang and Van Slyke,^[3] and by Saito and Tsutsui et al.^[4] Monochromatic displays based on such devices are reportedly due to be released on the commercial market in 1997 or 1998.^[5,6] Inorganic semiconducting and organic dye materials have to be deposited as thin films by the relatively expensive techniques of sublimation or vapor deposition, which are not well suited to fabrication of large-area devices. For these reasons, the possibility of using fluorescent conjugated polymers, which can be readily deposited from solution as thin films over large areas by spin-coating or doctor blade techniques, is most attractive. Considerable research efforts have gone into the development of electroluminescent polymers for use in LEDs, and in this review we aim to give an overview of the progress made in this area. Polymer LEDs are expected to have commercial applications as backlights

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[**] A list of abbreviations is given in the Appendix.

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for liquid crystal displays and as the emissive material in alphanumeric displays within the near future.

Aspects of the properties of conjugated polymers and organic electroluminescence have previously been reviewed. These reviews are listed in Table 1.

2. Poly(phenylene vinylene)s—A Case History

Electroluminescence in conjugated polymers was first discovered during investigations into the electrical properties of poly(1,4-phenylene vinylene) (PPV; 6),^[1] the simplest and cheapest poly(arylene vinylene).

2.1. The Synthesis of Poly(p-phenylene vinylene)—Precursor Polymer Routes

PPV (6) is a bright yellow, fluorescent polymer. Its emission maxima at 551 nm (2.25 eV) and 520 nm (2.4 eV) are in the yellow-green region of the visible spectrum. The polymer is insoluble, intractable, and infusible. Any synthesis of PPV directly from a monomer produces an insoluble material,

Table 1. Recent reviews on conjugated polymers and electroluminescence.

First author	Topic
May	polymer electronics ^[2]
Patil	optical properties ^[3]
Friend	polymer LEDs ^[4]
Bradley	electroluminescent polymers ^[5]
Holmes	EL in conjugated polymers ^[6]
Fox	light-emitting plastics ^[7]
Balgent	conjugated polymer EL ^[8]
Yan	polymer electronics ^[9]
Greenham	physics of conjugated polymers ^[10]
Gymer	organic EL displays ^[11]
Rothberg	organic EL ^[12]
Salbeck	EL with organic compounds ^[13]
Salbeck	conjugated polymer interfaces ^[14]
Sheets	organic EL devices ^[15]
Lovinger	organic transistors ^[16]
Feast	synthesis of conjugated polymers ^[17]
Yang	polymer EL and LECs ^[18]
Friend	polymer device structures ^[19]
Díaz-García	plastic lasers ^[20]
Deussen	organic LEDs ^[21]
Hild	photonic applications ^[22]

which cannot be easily processed; solution processing by spin-coating is, however, particularly desirable as it yields high-quality transparent thin films for the production of polymer

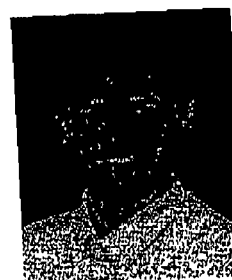
Andrew Holmes was born in Melbourne, Australia, in 1943 and received his early education at the University of Melbourne. He obtained his Ph.D. in 1971 in the field of annulene chemistry with Prof. Franz Sondheimer at University College London, and then carried out postdoctoral research at the Eidgenössische Technische Hochschule, Zürich with Prof. A. Eschenmoser on the total synthesis of vitamin B₁₂. In 1972 he was appointed University Demonstrator (Assistant Lecturer) and in 1977 Lecturer in the University Chemical Laboratory at the University of Cambridge. In 1989 he commenced a collaboration with Prof. R. H. Friend in molecular electronics, which led to the discovery of electroluminescence of poly(para-phenylene vinylene). Dr. Holmes has been the Director of the Melville Laboratory for Polymer Synthesis since 1994. Current research interests embrace the synthesis of functional macromolecules and biologically active natural products.



A. Holmes



A. Kraft



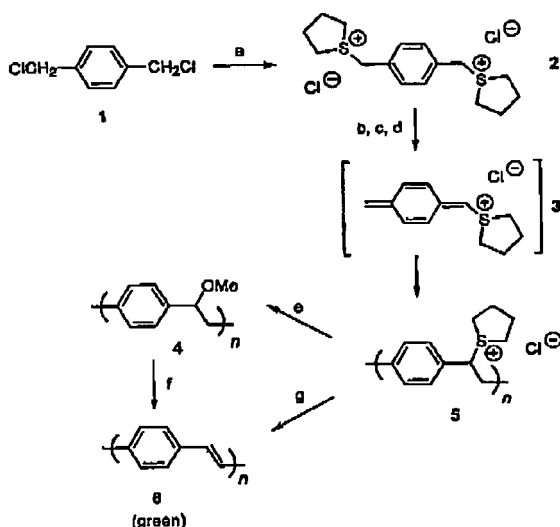
A. Grimsdale

Arno Kraft, born 1961 in Darmstadt, Germany, studied chemistry at the Universität Würzburg. He then worked in the group of Prof. M. Christl on the synthesis of and NMR spectroscopic investigations of benzvalene derivatives, and obtained his Ph.D. in 1989. After a brief stay with Prof. G. Erker, he joined Andrew Holmes as a postdoctoral research fellow. During the following three years he worked on the development of electroluminescent polymers and charge-transporting materials. He left Cambridge in 1993 to start independent research for his habilitation at the Universität Düsseldorf. His current interests include highly soluble and, at the same time, highly self-associating and self-assembling dendrimers and branched macromolecules.

Andrew Grimsdale, born 1963 in Waiouru, New Zealand, is a graduate of the University of Auckland. He worked on the synthesis of analogues of biologically active drimane sesquiterpenes with Prof. R. C. Cambie and obtained his Ph. D. in 1990. He then joined Prof. A. Pelter at the University of Wales in Swansea, where he investigated photochromic and electroactive organic materials. In 1994 he moved to Cambridge where he began research with Andrew Holmes into novel electroluminescent polymers. In 1997 he returned to Auckland.

EL devices. This dilemma is conveniently resolved by the use of a solution-processible precursor polymer. The sulfonium precursor route to PPV was introduced by Wessling and Zimmerman,^[24, 26] and was subsequently modified and optimized by other groups.^[27–29] The principle has been applied, not only to PPV and its derivatives, but also to a whole range of PPV-related copolymers.

Scheme 1 outlines the standard preparation of PPV (6).^[26] Treatment of 1,4-bis(dichloromethyl)benzene (1) with tetrahydrothiophene results in the formation of the bis-sulfonium



Scheme 1. Synthesis of PPV (6): a) tetrahydrothiophene, MeOH, 65 °C; b) NaOH, MeOH/H₂O or Bu₄NOH, MeOH, 0 °C; c) neutralization (HCl); d) dialysis (water); e) MeOH, 50 °C; f) 220 °C, HCl(g)/Ar, 22 h; g) 180–300 °C, vacuum, 12 h.

salt 2. Other sulfides such as dimethyl sulfide can be employed, but unwanted side reactions occur at sulfonio groups during subsequent steps.^[27] Polymerization of a methanolic solution of monomer 2 is induced by the addition of slightly less than 1 mol equivalent of aqueous sodium hydroxide at 0–5 °C. If more base is used, the resulting polymer solutions become brightly colored owing to partial base-induced elimination of the sulfonio groups. The mechanism of this polymerization deserves further investigation. Studies^[26, 30] have shown that the presence of radical trapping agents such as oxygen can severely lower the molecular weight of the polymer, which would suggest that the *p*-quinodimethane intermediate 3 undergoes radical polymerization, although anionic propagation cannot be completely excluded. The reaction is in practice best performed under an inert atmosphere and is terminated by neutralization with dilute hydrochloric acid. The almost colorless solutions of precursor polymer 5 are then dialyzed against distilled water to remove impurities having low molecular weight. The molar mass of the precursor polymer 5 cannot be determined easily by gel-permeation chromatography owing to the polyelectrolyte nature of the polymer. Treatment with refluxing methanol

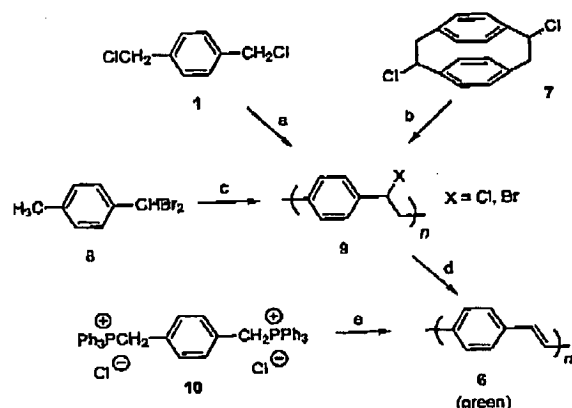
gives a neutral polymer 4 which on gel-permeation chromatography characterization shows a number-average molar mass M_n of $\geq 100\,000$ g mol⁻¹.^[31]

The precursor polymer 5 is converted into PPV (6) by heating thin films (spin-coated with thickness of typically 100 nm) in the temperature range of 180–300 °C for 12 h under vacuum (10^{-6} mbar).^[1, 26] Under these conditions the by-products of the elimination (tetrahydrothiophene and hydrogen chloride) escape easily. It has been reported that traces of oxygen during the conversion step reduce the luminescence quantum efficiency in the final PPV film. This has been attributed to the formation of carbonyl groups that are believed to quench luminescence.^[32–34] The formation of such groups was reported to be suppressed by performing the conversion in a reducing atmosphere of nitrogen and hydrogen.^[32–35] PPV prepared under these conditions has higher fluorescence and EL quantum efficiencies.^[35] Our own experience is that a nitrogen atmosphere suffices. When conducting the elimination step under argon, Schwöerer et al.^[36, 37] found that conversion already occurred at 160 °C. Vanderzande et al.^[38] and Müllen et al.^[39] then showed that the conversion temperature could be further reduced by using the bromide instead of the chloride salt of precursor polymer 5, which allows the conversion to occur at temperatures as low as 100 °C. This enables LEDs to be fabricated on flexible polymer foil substrates, for example on indium-tin oxide (ITO)-coated poly(ethylene terephthalate) (PET). Films of PPV can also be deposited by Langmuir–Blodgett techniques^[39] and by simple dip-coating. The resulting PPV shows remarkably good luminance properties given that these techniques contaminate PPV with surfactant residues.^[40–43] Highly aligned free-standing thin films and fibers of PPV can be formed by pre-ordering the precursor polymer 5 in a lyotropic liquid-crystalline phase before thermal conversion.^[44] This type of nanocomposite might show promise for polarized emission.

Other methods have also been exploited to prepare PPV suitable for LEDs. The materials produced by these routes, however, may differ from PPV prepared by the Wessling route in molar mass, molar mass distribution, film quality, nature and amount of defects and impurities, output of waste materials etc., and of course the resulting device efficiency and lifetimes may also vary considerably. A modified Wessling (quinodimethane) synthesis, based on the elimination of sulfinyl or sulfonyl groups instead of sulfonio groups, has been reported by Vanderzande et al.^[45–47] Galvin et al.^[48] favored a xanthate precursor polymer soluble in organic solvents and claimed that it gave better quality PPV films and higher device efficiencies than the standard route.

PPV films are also accessible by chemical vapor deposition (CVD) of compounds of type 1^[49] and 8 or of chlorinated cyclophane 7.^[50] In all cases the intermediate α -halo-precursor polymer 9 film is further converted to PPV 6 at 200 °C under vacuum (Scheme 2), but LEDs made with these films showed quite low (0.002 %) efficiencies (see Section 2.2).^[49, 51] Electropolymerization of 10 gave PPV films, but absorption and emission spectra were blue-shifted with respect to material produced by other methods, indicating that the electropolymerized material had a shorter conjugation

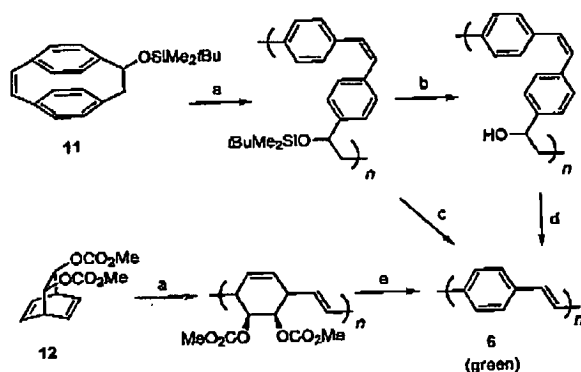
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Scheme 2. Alternative synthetic routes to PPV (6): a) 500–700 °C, 0.01 mbar; b) 580 °C, 10 Pa; c) 800–900 °C, 0.01 mbar, then 60 °C, 0.1 mbar; d) 200 °C, vacuum; e) CH_3CN , 5.5 V.

tion length owing to incomplete elimination of the phosphonio groups.^[72]

Ring-opening metathesis polymerization (ROMP) in principle offers the opportunity for precise control of polydispersity and microstructure. Applications to conjugated polymers such as polyacetylene are well-documented,^[21] and promising routes to PPV are also emerging. The siloxy-substituted cyclophane 11^[23] or bicyclic monomer 12^[24] are typical substrates for ROMP and afford well-defined precursor polymers, which are converted to PPV 6 by thermal elimination (Scheme 3).



Scheme 3. ROMP routes to PPV (6): a) $[\text{Mo}(\text{=NAr})(\text{=CHCMe}_2\text{Ph})][\text{OCMe}(\text{CF}_3)_2]_2$; b) Bu_4NF ; c) $\text{HCl}(\text{g})$, 190 °C; d) 105 °C; e) 280 °C.

2.2. Simple Electroluminescent Devices Based on PPV—A Basic Polymer LED

As a material, PPV has several advantages over classical inorganic light-emitting semiconductors. First the ease of processing permits PPV to be spread onto large areas and curved surfaces. Second PPV shows the tensile properties expected for a chain-extended polymer: its elastic moduli and

tensile strength are almost as high as those of polyamide fibers. This, of course, helps the polymer “to survive” under the harsh conditions prevailing during device operation.

In a light-emitting diode (LED) or electroluminescent device (Figure 1), the thin film of light-emitting material is sandwiched between two electrodes, one of which has to be

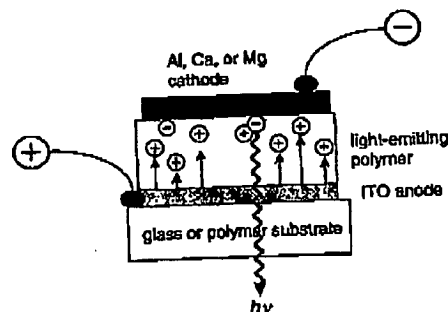


Figure 1. Schematic drawing of a single-layer electroluminescent device. An applied electric field leads to injection of holes (positive charges; the majority charge carriers in polymers such as PPV) and electrons (usually the minority charge carriers) into the light-emitting polymer film from the two electrode contacts. Formation of an electron-hole pair within the polymer may then result in the emission of a photon. Since holes migrate much more easily through PPV than electrons, electron-hole recombination takes place in the vicinity of the cathode.

semitransparent. Under an applied bias (voltage), oppositely charged carriers (electrons and holes) are injected into the emissive layer(s) from the opposing contacts, and are swept through the device by the high ($>10^5 \text{ V cm}^{-1}$) electric field. Some of the electrons and holes combine within the emissive material to form triplet and singlet excited states. The singlets are indistinguishable from the excited states of photoluminescence (PL), the fluorescence process resulting from photoexcitation of the ground state (Figure 2).

A common measure of the efficiency of electroluminescent devices is the number of photons emitted per electron injected. This is the internal efficiency, which is based on the assumption that all the light generated is received by the viewer. External efficiencies are a factor of $2n^2$ smaller than internal efficiencies, where n is the refractive index of the polymer.^[55] For a polymer having a typical refractive index of 1.4 this factor would be four, and external quantum efficiencies for the current family of polymers fall within the range 0.1–5%.

It should also be noted that EL efficiencies are dependent on the distance of the emitting dipoles from the metal electrode.^[56] Power conversion efficiencies (W W^{-1}) are quoted by device engineers. These values are reached by multiplying the external quantum efficiency by the ratio of the photon energy and the drive voltage. The power efficiency should be as high as possible in order to maximize device longevity, and, at the same time, devices have to be bright at low current and low electric field. The luminous efficiency (lm W^{-1}) is the power conversion efficiency multiplied by the luminous efficacy (in lumens per watt).^[57] The luminous efficacy is a conversion factor that takes account of the fact

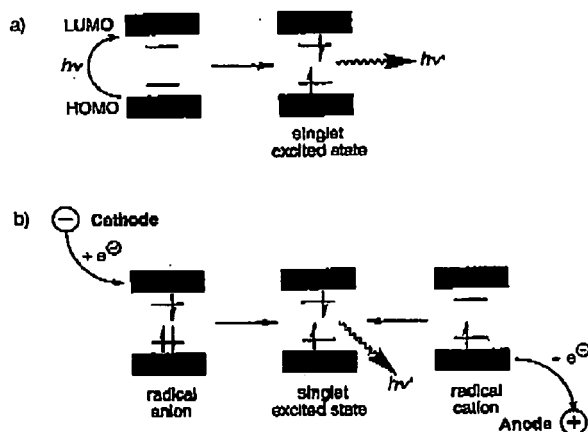


Figure 2. a) Irradiation of a fluorescent polymer excites an electron from HOMO to LUMO. In a typical conjugated polymer, two new energy states are generated upon relaxation within the original HOMO–LUMO energy gap and are each filled with one electron of opposite sign (singlet excited state). The excited polymer may then relax to the ground state with emission of light at a longer wavelength than that absorbed (photoluminescence). b) In a polymer LED, electrons are injected into the LUMO (to form radical anions) and holes into the HOMO (to form radical cations) of the electroluminescent polymer. The resulting charges migrate from polymer chain to polymer chain under the influence of the applied electric field. When a radical anion and a radical cation combine on a single conjugated segment, singlet and triplet excited states are formed, of which the singlets can emit light.

that the eye is more sensitive to green than to red and blue light. Current values reported for luminous efficiencies range between $1\text{--}2\text{ lm W}^{-1}$, and values as high as 10 lm W^{-1} for the best devices have been reported. Luminance (cd m^{-2}) and luminance per unit of current density are also measures of device efficiency. Typical luminances for laptop displays are about 100 cd m^{-2} , but much higher luminances would be required for a matrix addressing scheme that avoids the need for thin film transistors behind each pixel.

The choice of the correct electrode combination is crucial to the operation of a polymer light-emitting diode (Figure 1). There has been considerable progress in understanding the dopant behavior of negatively charged metal contacts at the metal–polymer interface.^[18] Single-layer devices are typically fabricated by solution-coating a thin film of polymer on indium–tin oxide (ITO)–glass and by vacuum evaporation of a cathode. These device structures will be denoted as ITO/polymer/metal in the remainder of this review. An early device configuration ITO/PPV/Ca had an average internal efficiency of 0.1%.^[57, 58] Glass or PET substrates with a thin (ca. 15 nm) transparent ITO layer are commercially available. The mixed-metal oxide has a high work-function, which matches the HOMO energy level of PPV and makes it convenient for hole injection (i.e. removal of an electron from the HOMO) into the polymer.

Other metals and oxides such as gold,^[11] $\text{Al}/\text{Al}_2\text{O}_3$,^[11] and SnO_2 ^[59] have also been tested for electroluminescent polymers but in only a few cases gave better performance. Calcium as a result of its reactivity (especially its moisture sensitivity)

may not be the preferred electrode for use in commercial devices unless excellent encapsulation can be realized, and a less reactive low-work-function metal would generally be favored. Aluminum has been a compromise, but the internal efficiency of a PPV light-emitting device using ITO and Al electrodes is only 0.01% owing to poor electron injection.^[57] Introduction of a thin layer of aluminum oxide between the PPV and Al layer (i.e., $\text{Al}/\text{Al}_2\text{O}_3$ as cathode) can result in a marked improvement in device efficiency as a result of carrier confinement.^[60]

Heterostructure LEDs made from self-assembled multilayers of PPV and polyanions such as sulfonated polyaniline have also been constructed and found to emit bright yellow-green light with low turn-on voltages.^[61–66] The self-assembled multilayer technique so far seems to enable exceptional control of the device thickness, and has recently been extended to include ruthenium-based complexes.^[67] The improvement of power efficiency and stability of EL devices by addition of an extra charge-transporting layer between the PPV and the cathode^[58, 68–71] is discussed in Section 3.2.

2.3. Solution-Processible Poly(phenylene vinylene)s—Direct Deposition of Electroluminescent Polymers

Following the discovery of electroluminescence in PPV, LEDs from PPV derivatives that are soluble in the conjugated form were reported independently by Ohnishi et al. at Sumitomo,^[72] and by Braun and Heeger at Santa Barbara.^[73, 80] Such soluble polymers no longer require thermal treatment during device fabrication, which is the drawback of the PPV precursor route, although they tend to have lower glass transition temperatures. It should be pointed out that, while the precursor polymer 5 is usually processed from methanolic solutions (and, like PPV, does not dissolve or swell in chloroform), almost all soluble PPV derivatives used in EL devices are processible from solvents that do not cause swelling of PPV or its precursor polymer 5. This difference in solubility can be applied advantageously to the design of multilayer devices that consist of sandwich structures with layers of different polymers, for example, PPV and substituted PPVs (Section 3.3.).^[64, 82]

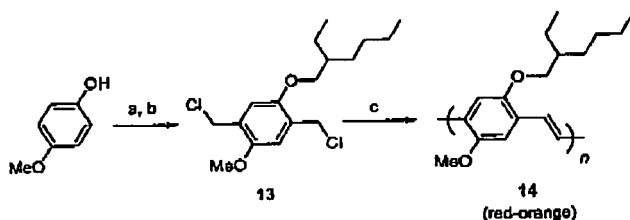
Poly[(2,5-dialkoxy-1,4-phenylene)vinylene]s with at least one long, solubilizing alkoxy side chain (e.g., 2-ethylhexyloxy, 3,7-dimethyloctyloxy, 2-methylpentyloxy, or dodecyloxy)^[76, 77, 83–87] dissolve in various organic solvents such as chloroform or tetrahydrofuran. In addition, their emission maximum is red-shifted [to ca. 590 nm (2.1 eV)] compared with that of PPV. The long side chains, which keep the conjugated polymer backbones apart from each other, apparently have a beneficial effect on the polymers' fluorescence and electroluminescence quantum yields.

Dialkoxy-substituted PPVs can be prepared by a sulfonium precursor route as described for the synthesis of PPV.^[24, 84, 88–90] Although the Wessling route may be used to make soluble PPV derivatives, a dehydrohalogenation–condensation polymerization, first developed by Gilch et al.,^[91] is generally preferred. It proceeds through base-promoted 1,6-elimination of 1,4-bis(halomethyl)benzene derivatives.^[78, 84, 85, 92]

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This shortens the preparation of the conjugated polymer by two steps, and can result in substantially increased yields. As with the Wessling procedure, the polymerization mechanism could involve a quinodimethane, an anionic intermediate, or a carbenoid species. Molar masses of soluble poly[(2,5-dialkoxyphenylene)vinylene]s, obtained by the polymerization of bis(chloromethyl) compounds with potassium *tert*-butoxide, are comparable to those obtained by the sulfonium precursor route.

Scheme 4 shows the synthesis of the most studied dialkoxy-PPV: MEH-PPV (14).^[84, 85] The branched side chain in MEH-PPV has a favorable effect on the solubility of the polymer—



Scheme 4. Preparation of MEH-PPV (14): a) 3-(bromomethyl)heptane, KOH, EtOH, reflux, 16 h; b) RCHO, concd. HCl, dioxane, 20 °C, 18 h, reflux, 4 h; c) KO^tBu, THF, 20 °C, 24 h.

indeed, the polymer dissolves easily in solvents such as tetrahydrofuran, chloroform, or xylene. A related polymer 17 (OC₁C₁₀-PPV) with a 3,7-dimethyloctyloxy side chain has been the subject of investigation by workers at Philips and Hoechst.^[17]

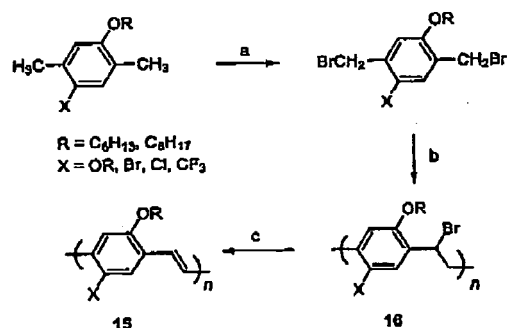
The bis(chloromethyl) compound 13 is synthesized by alkylation of 4-methoxyphenol followed by chloromethylation.^[79, 83, 84, 86] Polymerization of the monomer 13 is induced with a tenfold excess of potassium *tert*-butoxide in tetrahydrofuran and gives the bright red-orange MEH-PPV (14). Careful control of concentration is needed to avoid gelation. Purification involves several reprecipitations in methanol. A simple electroluminescent device (ITO/MEH-PPV/Ca) already achieves a quite respectable efficiency of 1.0%.^[79, 83] Insertion of a thin hole-blocking layer of poly(methyl methacrylate) film by Langmuir–Blodgett deposition is reported to give up to a fourfold increase in quantum efficiency with aluminum cathodes.^[84] Devices have also been constructed with doped silicon as anode, thus opening the possibility of integrating polymer LEDs with silicon-chip technology.^[88, 90]

Most of the reports of polymer LEDs described ITO on glass as the hole-injecting contact. Polyaniline (PANI), a long-known conducting polymer, presents an interesting alternative to ITO in devices using MEH-PPV, as, although it is deeply colored, it has an optical window coinciding with the maximum of emission for MEH-PPV. Using a layer of acid-doped PANI on ITO reduces the drive voltage of the device and causes an increase in device efficiency by a factor of 30%. Such devices can produce peak luminances of over 10 000 cd m⁻² at drive voltages of 5 V, with external quantum efficiencies of 2–2.5%, and luminous efficiencies of 3–

4.5 lm W⁻¹.^[97] Furthermore, replacement of the ITO-coated glass substrate by a polyaniline-coated PET sheet enables the manufacture of a flexible electroluminescent device.^[98, 99] As the PET/PANI/MEH-PPV/Ca device consists of flexible polymers (with the exception of the calcium cathode), it can be safely deformed even during operation (inside a glove box). While this is an interesting application of PANI, it should be noted that ITO-coated PET is commercially available as an alternative flexible anode of reasonable mechanical stability.^[84] A cylindrical polymer LED with layers of a transparent polyaniline electrode and MEH-PPV wrapped around a cylindrical metal cathode has been constructed; in this example the reactive electrode is protected by a sandwich of polymers.^[99]

A significant recent development has been the introduction of a sulfonic acid-doped polyethylenedioxythiophene conducting polymer either in combination with ITO glass or alone as an anode. Quite spectacular improvements in device efficiency and reduction in drive voltage are observed in two-layer devices fabricated with this material.^[100, 101] Gel-processing of a blend of MEH-PPV in polyethylene gives access to oriented films that show anisotropies of 60:1 in their fluorescence emission spectra; the preferred direction of emission is parallel to the draw axis.^[102, 103] Rubbing alignment of a poly(dialkoxyphenylene vinylene) is the most effective way of orienting material to achieve polarized EL.^[104, 105] Such oriented emission might find use for back-lighting in a liquid-crystal display. Orientation is also possible using Langmuir–Blodgett techniques for film deposition.^[105]

Electroluminescent poly(2,5-dialkoxy-1,4-phenylene vinylene)s other than MEH-PPV have been similarly prepared.^[85, 86, 106, 107] If less than one equivalent of base is used, a soluble α -halo precursor polymer 16 is obtained that can be converted into the conjugated polymer 15 (Scheme 5)^[85, 108]—

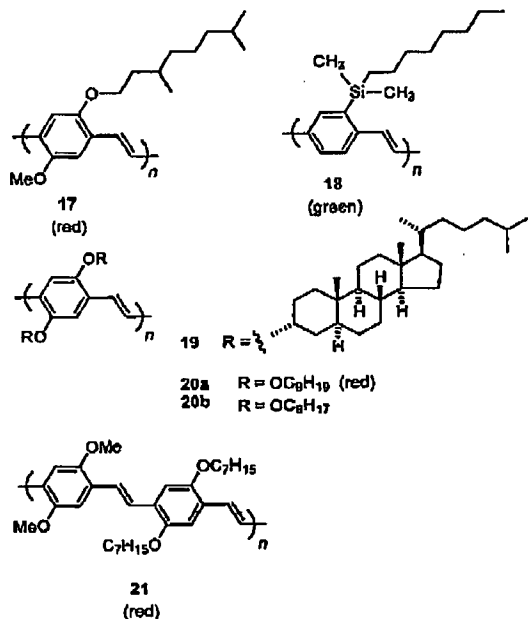


Scheme 5. The halo-precursor route to substituted PPVs: a) NBS, CCl₄, h ν ; b) KO^tBu, THF; c) 160–220 °C, vacuum, 4 h.

this is known as the halo-precursor route and has some advantages if the precursor polymer is more soluble, if vapor deposition methods are used, or if incomplete conversion to a partially conjugated polymer is envisaged (Section 3.1).

Branched side chains, as in MEH-PPV, generally enhance solubility more than linear ones of identical length and number of carbon atoms or heteroatoms. With increasing size

of the alkoxy group, EL efficiency passes through a maximum and decreases again with even larger side chains;^[78] very large substituents, for example cholestanoxy as in **19**,^[106, 109] seem to overpower and "dilute" the semiconducting properties of the conjugated polymer (Scheme 6). The highest external EL



Scheme 6. Examples of soluble, dialkoxy-substituted PPV derivatives.

efficiency reported to date for a single layer device using dialkoxy-substituted PPV derivatives is 2.1 % for a device made by Philips with **17**.^[77] This polymer EL device has a luminance of 100 cd m⁻² with a luminous efficiency of 3 lm W⁻¹ at a drive voltage of 2.8 V. A group at Hoechst has achieved the same quantum efficiency and luminance with a flexible device using an ITO anode on PET, with a slightly lower luminous efficiency of 2 lm W⁻¹ at a driving voltage of 3.4 V and a current density of 4.5 mA cm⁻².^[17] The introduction of a silyl group as in DMOS-PPV (**18**) widens the band gap so as to give emission of green light.^[110-114] Yoshino et al.^[115] have employed poly(2,5-dinonyloxy-1,4-phenylene vinylene) (**20a**), which forms a nematic liquid-crystalline state upon melting. When cooled to room temperature, the polymer remains oriented and has a lower energy gap (2.08 eV) than in an unoriented film (2.21 eV) formed by casting from chloroform solution. Rubbing of a film of this material also induces molecular orientation, and gives rise to oriented electroluminescence.^[116] This technique has also been applied to a smectic liquid-crystalline copolymer of distyrylbenzene linked by long chain polyester flexible spacer groups.^[117]

Other polycondensations have been used to prepare soluble PPV derivatives. Wittig condensation of terephthalaldehydes with arylene-bisphosphorylidenes furnishes alternating PPV copolymers.^[118] An alkoxy-substituted PPV copolymer (**21**) prepared in this manner was found to show

orange (585 nm) emission.^[118] Similar PPV copolymers have been prepared by Heck coupling of dihalobenzenes with divinylbenzenes.^[119]

3. Improvement of Device Efficiency—Making EL Polymers Competitive

High efficiencies and reliability are the principle requirements of molecular and polymeric light-emitting materials for commercial applications.^[19] The optimum goal is to obtain maximum power efficiency and brightness at minimum drive voltage and current density. This combination should afford devices having long lifetimes. The improvement of EL devices therefore requires optimization of the electroluminescent polymer and/or the device structure. Whereas it took about thirty years for an inorganic semiconductor to reach luminous efficiencies of several lm W⁻¹, organic light-emitting polymers have reached this level of performance in less than ten years. It is evident that the efficiencies of molecular and polymer organic LEDs have been dramatically improved in a short time, and are beginning to compete with those obtained for conventional inorganic LEDs.

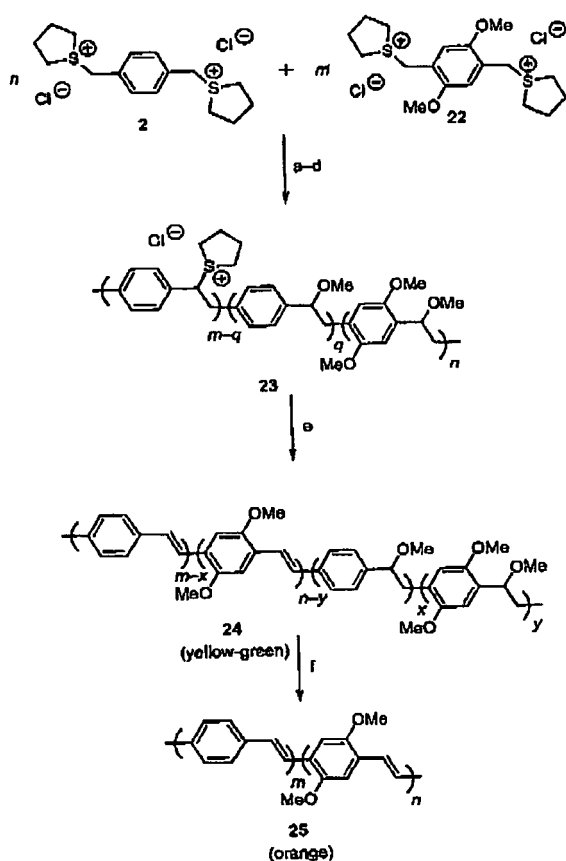
3.1 The Use of Copolymers—Finessing the Properties

For the majority of conjugated polymers investigated so far, electron injection has proved to be more difficult than hole injection, that is, the polymers are more easily oxidized than reduced. This has been largely remedied by the use of metals with a low work-function (especially Ca) as the cathode material. However, calcium is highly susceptible to atmospheric degradation. Although this can be retarded by encapsulation, it would be beneficial to use less moisture- and oxygen-sensitive metals. If the barrier for electron injection from such metals is to be lowered, the polymer must be modified so that the energy of its LUMO matches the work function of the cathode. Copolymers of one kind or another present an attractive solution to this problem.

Copolymers containing a combination of different arylene units can be much more versatile than homopolymers and may even be chemically tuned to provide a range of materials with considerably improved EL properties. This was for the first time exemplified by statistical copolymers of PPV and poly[(2,5-dimethoxy-1,4-phenylene)vinylene], although other copolymers having interrupted conjugation have also been investigated.^[57, 120-123]

By a modification of the sulfonium precursor route the two monomers **2** and **22** are copolymerized in the presence of sodium hydroxide in a water-methanol mixture (Scheme 7). The ratio of the units in the resulting (presumably statistical) copolymer **23** depends on the feed ratios of the two sulfonium salt monomers. The use of a solvent mixture leads to selective substitution of the sulfonio groups by methoxy groups. This occurs at a faster rate at those benzylic carbon atoms that are attached to the more activated dimethoxyphenylene rings. As a result, copolymer **23** has two leaving groups at the benzylic carbon atoms; the methoxy groups are adjacent to all the dimethoxyphenylene and a few phenylene units, and sulfonio

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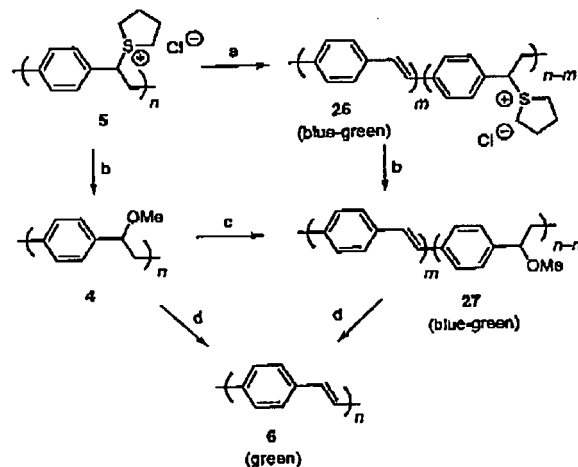
Scheme 7. Synthesis of PPV/dialkoxy-PPV copolymers: a) NaOH, MeOH/H₂O, 0°C, 1 h; b) HCl; c) dialysis (water); d) MeOH; e) 220–300°C, vacuum, 12 h; f) 220°C, HCl(g)/Ar, 22 h.

groups are next to most of the phenylene units. Thermal conversion of thin (typical thickness 100 nm) films of 23 results in complete elimination of the sulfonio and only partial elimination of the methoxy leaving groups, which gives polymer 24 with interrupted conjugation. Complete elimination of all leaving groups to furnish the fully conjugated polymer 25 requires thermolysis under acidic conditions.

The electroluminescent device efficiency of polymer 24 varies with the composition of the copolymer and has its peak with a copolymer prepared from a 9:1 feed ratio of salts 2 and 22. The maximum internal efficiency in this case is 0.3%, demonstrating a 30-fold improvement compared with that of PPV (0.01%) in the same device configuration (Al–Al₂O₃/polymer/Al).^[122, 124] The shortening of the conjugated segments actually improves fluorescence yields and electroluminescence efficiency, probably originating from a reduction in nonradiative processes such as diffusion of the excited states to quenching sites. On the other hand, a large fraction of interruptions in the conjugated chain will lower the mobility of charged carriers. Somewhere in between lies an optimum for electroluminescence efficiency. The principle has been applied to other copolymers.^[123] Alkoxy- and alkyl-substituted

poly(phenylene vinylene)s prepared by the dehydrohalogenation route also yield interrupted copolymers having relatively high EL efficiencies.^[123] In addition, statistical copolymer 23 has found use in forming lithographically patterned copolymers and waveguides.^[120, 121]

A simple modification of the PPV synthesis gives access to PPV-derived blue-shifted light-emitting polymers with a high concentration of interruptions in the conjugated chain. Partial conversion of precursor homopolymers 4 or 5 produces statistical copolymers 26 and 27 with regions of saturated and unsaturated units (Scheme 8).^[125, 126] The conversion of



Scheme 8. Synthesis of partially conjugated PPV copolymers: a) Bu₄NOH, MeOH; b) MeOH, 50°C; c) 300°C, vacuum, 12 h; d) 220°C, HCl(g)/Ar, 22 h.

sulfonium precursor polymer 5 to 26 may be accomplished by either thermal or base treatment. Although 26 is prone to further elimination, Heeger et al. have found that conversion at 160°C for 2 h gave a copolymer of the type 26 with fairly good long-term stability and emission efficiency.^[127]

Another approach to raising the efficiency of PPV is the introduction of disorder into the chain, thus interfering with polymer chain packing. Son et al.^[128] have synthesized amorphous PPV by using a modified Wessling procedure with a xanthate leaving group. The resulting PPV has a mixture of *cis*- and *trans*-alkene units, which affects conjugation and interferes with packing. Internal efficiencies of up to 0.22% for single-layer devices with aluminum cathodes and 2% for double-layer devices using an electron-transporting layer (see Section 3.2) are reported. It is not clear whether the improvements in efficiency arise from interruptions to conjugation or from reduced intermolecular order owing to the presence of Z double bonds. The authors favor the latter explanation.

Hörhold et al. have reported poly(arylene vinylene)/poly(phenylene vinylene) alternating copolymers in which the arylene substituent carries in-chain phenylamino groups. These have the effect of dramatically reducing the oxidation potential compared with that of PPV-based polymers (and are therefore photoconductors), and offer interesting possibilities as electroluminescent materials as well.^[129]

3.2. Multilayer Devices—Raising Device Efficiency with Additional Charge-Transporting Layers

The electroluminescent conjugated polymer devices discussed so far were mostly single layer devices, that is, they have the conjugated polymer sandwiched directly between anode (high work-function electrode) and cathode (low work-function electrode). Unless the barriers between these contacts and the HOMO (or LUMO) of the polymer are identical or zero, one type of charge carrier (either holes or electrons) will be preferentially injected. For a discussion of factors affecting charge injection the reader is referred to the article by Blom et al.^[130] and the excellent reviews by Greenham and Friend,^[34] and Sheats et al.^[12]

For PPV, the injection of holes predominates. To increase the efficiency of devices, electron injection has to be significantly boosted. The use of certain additional layer(s) of materials can promote the passage of electrons through the layer and, at the same time, provides a barrier to the passage of holes. Such a layer is called an electron-conducting/hole-blocking (ECHB) layer. A suitable ECHB material should have an electron affinity equal to or greater than the electron affinity of PPV. As illustrated by Figure 3, holes are increas-

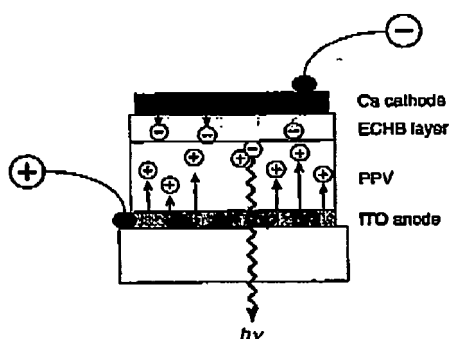
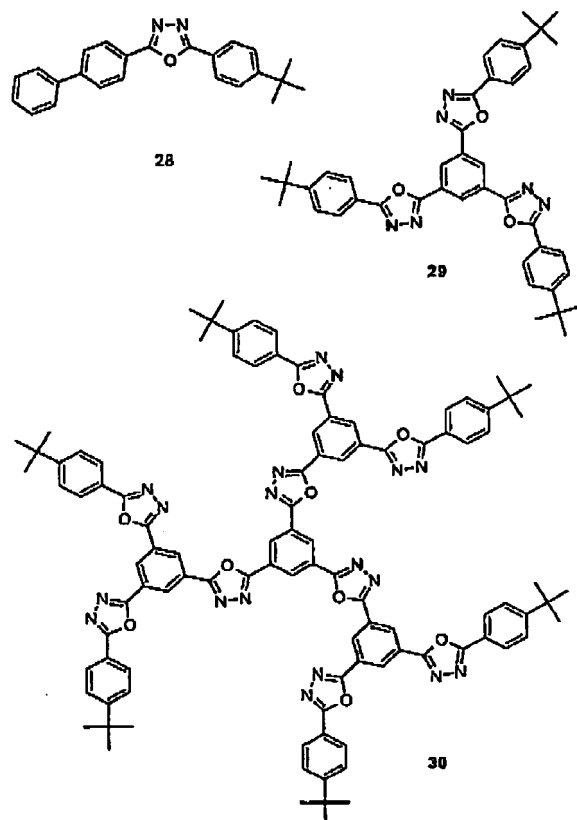


Figure 3. In this improved bilayer device structure for a polymer LED an extra ECHB layer has been inserted between the PPV and the cathode metal. The ECHB material enhances the flow of electrons but resists oxidation. Electrons and holes then accumulate near the PPV/ECHB layer interface. Charge recombination and photon generation occur in the PPV layer and away from the cathode.

ingly confined in the PPV layer, and the site of recombination of holes and electrons (where the emission takes place) is then moved away from the metal-polymer interface, which is known to act as a quenching site. In contrast, hole injection is not a problem with devices made from PPV. When a device with a hole-transporting layer (between the anode and the PPV layer) was tested, the efficiency of the device actually decreased, indicating that the main limiting factor in PPV-based LEDs is indeed electron injection and transport.^[131]

The principle behind the design of ECHB materials is well exemplified by oxadiazoles, the first and most extensively investigated class of ECHB materials. Following the successful use of 2-(4-biphenyl)-5-(4-*tert*-butylphenyl)-1,3,4-oxadiazole (PBD) (28) in sublimed film EL devices,^[3, 4] PBD has long been a favored compound (Scheme 9). Oxadiazoles



Scheme 9. Examples of oxadiazole-containing electron-transporting materials.

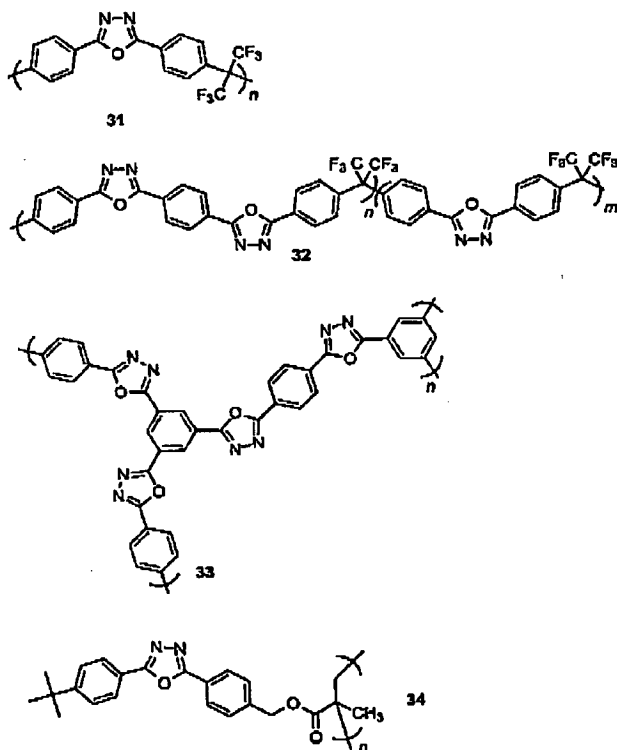
are electron-deficient, making PBD an extremely poor hole acceptor. It has a number of advantages; it is available in high purity, sublimates, can be spin-coated as a dispersion in a range of standard polymers such as poly(methyl methacrylate) (PMMA),^[68] and can be blended with electroluminescent polymers.^[112, 122-124] However, some incompatibilities with polymers exist that may lead to phase separation or crystallization especially at higher temperatures. Crystallization may be retarded by using a solid dispersion of PBD in an insulating polymer (PMMA).^[68] As the ITO/PPV/PBD-PMMA/Ca device then becomes thicker owing to the extra layer, the voltage required to drive the device needs to be increased. This drawback is outweighed by a rise in internal BL efficiency from 0.1 % (for an ITO/PPV/Ca device) to 0.8 % (for ITO/PPV/PBD-PMMA/Ca). However, higher current densities cause a drop in device efficiency as a result of quenching by the high amount of accumulated holes at the PPV/PBD-PMMA interface.

The incorporation of identical redox sites within the same molecule has been used successfully in the design of charge-transporting compounds for electrophotography (photocopiers and laser printers). Since electron hopping is the main charge-transport mechanism in ECHB materials, increasing the number of (in this case) oxadiazole units would therefore

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seem a promising way to improve the charge-transporting properties.^[135] The idea was extended to the design of branched and highly symmetrical compounds such as the radialene 29,^[136] starburst structures,^[137,138] and small dendrimers like 30.^[138,139] These materials have high glass-transition temperatures and form stable glasses, which minimize the problems of crystallization. Although the large numbers of branches in these materials should have made electron-transfer more efficient because of enhanced charge migration opportunities, they have not shown any improvement over PBD.

While low molar mass compounds are much easier to purify, incorporation of the active electron-transporting moieties into amorphous polymers should at least mitigate the problem of crystallization. Several polymeric analogs of PBD have been prepared with the oxadiazole unit either in the main or the side chain. A number of examples of poly(aromatic oxadiazole)s with satisfactory performance have been reported.^[70,72,74,136,140] Solubility is mainly influenced by the frequency of solubilizing flexible spacer groups as in 31, or the use of copolymer structures as in 32 (Scheme 10). A hyperbranched oxadiazole polymer 33, which

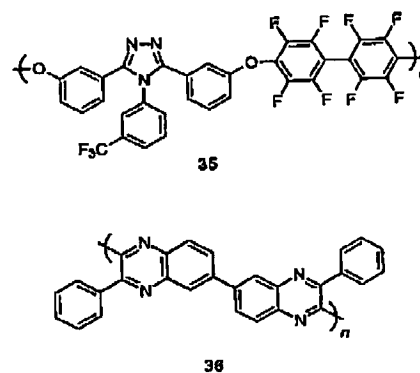


Scheme 10. Examples of oxadiazole-containing electron-transporting polymers.

is soluble in trifluoroacetic acid, was prepared by a one-step procedure, but its electron-transporting properties were mediocre, perhaps caused by defects within the polymer.^[134]

Poly(methacrylate)s with ECHB-active oxadiazole side chains (e. g., 34) have been prepared by radical polymerization and show good film-forming properties.^[72,141-143] However, their device performance has not fulfilled expectations, as higher drive voltages are required to achieve the improvement in efficiency.

Since oxadiazoles have not proved entirely successful as ECHB materials, attention has turned to other classes of materials. Nitrogen heterocycles such as 1,2,4-triazoles, 1,3,5-triazines,^[32,9] or quinoxalines are of particular recent interest. The turn-on voltage in devices with an ECHB layer consisting of the polymer 35, which contains a 1,2,4-triazole unit, is surprisingly unaltered from LEDs without an electron-transporting layer (Scheme 11).^[69,76] The electron-deficient nitro-



Scheme 11. Examples of a triazole- and a quinoxaline-containing electron-transporting polymer.

gen atoms in poly(phenyl quinoxaline) (36) also enhance the electron affinity of the polymer. This material has been shown to greatly enhance the efficiency of devices that use soluble PPV derivatives.^[144] The materials discussed above have undoubtedly made a significant contribution towards improvement in device efficiency. A more successful approach may be to increase the electron affinity of the emissive polymer as will be discussed in Section 4.

3.3. Multilayer Devices with More Than One Electroluminescent Polymer—Towards White Light Emission

Other multilayer devices than those discussed in Section 3.2 can be constructed from at least two electroluminescent polymers. If carefully chosen, they show light emission from more than one layer provided that the polymers have small and controlled variations in energy gap from one layer to the next. This is necessary to avoid any build-up of space-charge at the interfaces between polymer layers. The first example of this type of LED consisted of an ITO/MEH-PPV/PPV/copolymer 24/Ca device.^[81] When one polymer is coated on top of another polymer layer, it is important that the process does not cause swelling or dissolution of the already deposited layer, and that good quality interfaces are obtained. Since

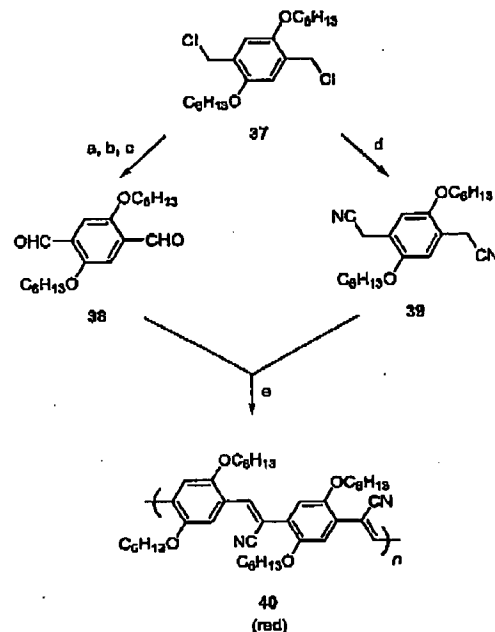
PPV and the sulfonium copolymer precursors are insoluble in chloroform, and MEH-PPV is insoluble in methanol, such a multilayer structure could be produced by spin-coating successive layers onto ITO without intermixing between MEH-PPV and the precursor layers. The precursor polymers 5 and 23 were then converted into the conjugated polymers and, after deposition of calcium, the device emitted orange light with the emission spectrum stretching from 800 nm (1.55 eV) through to 490 nm (2.5 eV). It was therefore concluded that electroluminescence occurred from both the red-light-emitting MEH-PPV, which was furthest away from the cathode, and from PPV, which showed yellow-green EL. The broadening of the emission spectrum further suggested how, in principle, to fabricate a white light source from a sandwich of several EL layers. A more recent multilayer device design developed by Yoshino et al.^[145-147] uses layers of the blue-emitting polymer 75a and of red-emitting materials such as the poly(3-alkylthiophene) 49a separated by a charge-transport layer. Depending on the bias either red or blue light is emitted, while under alternating current bias emission from both materials is observed.

4. Polymers with Higher Electron Affinity—Luminescent Transport Layers

The ideal light-emitting polymer should be both fluorescent and avoid the need for an extra electron-transporting material. It should also function with cathode metals other than calcium. Calculations^[148] have shown that a cyano substituent (and presumably other electron-withdrawing groups) on the ring or vinyne moiety of PPV lowers the HOMO and LUMO energies and increases the electron affinity of the polymer, thus improving the efficiency of electron injection and the potential efficiency of a polymer LED. Unfortunately, the Wessling (quinodimethane) route to poly(arylene vinylene)s is unsatisfactory when electron-withdrawing substituents are involved, and alternative polymerization or polycondensation methods need to be employed.

4.1. CN-PPV—Highly Luminescent Electron-Deficient Polymers

CN-PPV (40), a dialkoxy-substituted PPV derivative with cyano-groups on the vinylene units should be regarded as an alternating copolymer in this context. It is readily available by a Knoevenagel condensation^[149] between equimolar amounts of the terephthalaldehyde 38 and the benzene-1,4-diacetonitrile derivative 39, both obtained from the same starting material 37. The condensation reaction takes place upon addition of excess tetrabutylammonium hydroxide (or potassium *tert*-butoxide) in a tetrahydrofuran/*tert*-butanol mixture at 50 °C (Scheme 12).^[150] Polymer 40 precipitates and can be easily isolated. Careful control of reaction conditions is required to avoid Michael additions (and consequently crosslinking), which may lead to polymers with inferior EL properties, and purification by reprecipitation is essential to obtain high quality polymer. CN-PPV is a brilliant



Scheme 12. Synthesis of CN-PPV (40): a) NaOAc; b) KOH, EtOH; c) pyridinium chlorochromate; d) NaCN; e) KO^tBu or Bu₄NOH, tBuOH, THF, 50 °C.

red, fluorescent material with a molar mass typical for polycondensates.

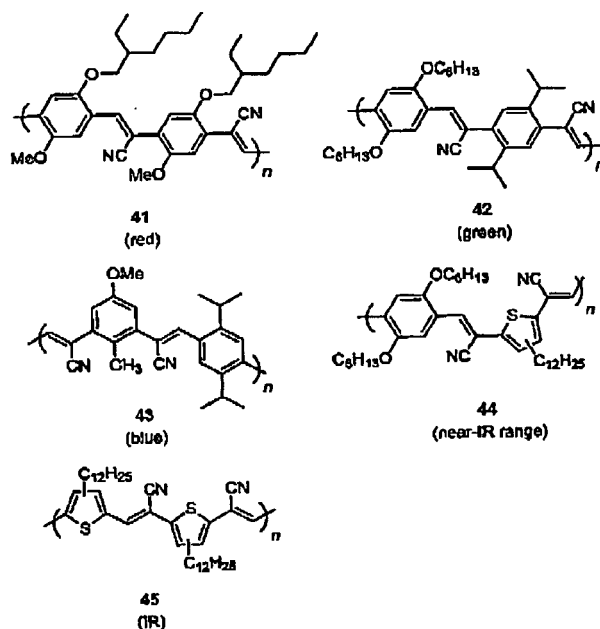
The HOMO–LUMO gap of CN-PPV (590 nm; 2.1 eV) is mainly determined by the effect of the alkoxy substituents, which also serve to promote solubility in chloroform, and thus ensure processibility of the conjugated polymer; the cyano substituents contribute only to an increase in the electron affinity of the polymer compared with PPV. Cyclic voltammetry studies show that the cyano groups shift the onset of reduction by about 0.6 V.^[150] The low HOMO–LUMO gap of CN-PPV also indicates that the nitrile groups do not introduce any significant steric torsion in the conjugated poly(2,5-dialkoxyphenylene vinylene) chain.

Internal efficiencies of red-emitting ITO/CN-PPV/cathode devices can reach 0.2% with calcium as well as aluminum cathodes. This is particularly noteworthy because other conjugated polymers such as PPV suffer from at least a tenfold reduction in efficiency when the electron-injecting contact is changed from Ca to Al. Since CN-PPV shows much higher electron affinity than PPV owing to the introduction of cyano groups, the device efficiency is now determined by hole injection at the ITO electrode. As a result of this, the introduction of a hole-transporting layer improves EL efficiencies considerably. PPV is a suitable hole-transporting polymer, and CN-PPV can be easily spin-coated on top of an insoluble PPV layer. Two-layer electroluminescent ITO/PPV/CN-PPV/cathode metal devices operate with very high internal (4%) efficiencies.^[151, 152] Significant lifetimes were only observed with high-quality polymer, demonstrating once more the importance of purification. The emission (λ_{max} =

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710 nm) occurs exclusively from the lower energy CN-PPV, with no evidence of electroluminescence from the PPV layer. Although this appears to be in contrast to the multilayer devices discussed in Section 3.3, CN-PPV apparently acts more like a sink for charge carriers and excited states rather than to permit any emission from another EL polymer (namely PPV) to occur.

The synthetic route is extremely flexible and lends itself to considerable variation, enabling the synthesis of many other α -cyano PPV derivatives (Scheme 13).^[123, 153] Some of these



Scheme 13. Color range available for CN-PPV derivatives.

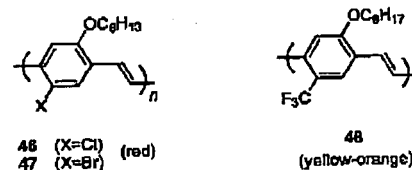
show similarly high emission efficiencies in double-layer devices with PPV.^[12, 154] In particular, MEH-CN-PPV (41) is processible in solvents such as toluene and exhibits very high EL device efficiencies. The improvement in processibility clearly contributes significantly to the improved device efficiency. A double layer device ITO/PPV/41/Al produces red-orange (600 nm) light with a power efficiency of 5 cd A⁻¹ corresponding to a luminous intensity of over 1000 cd m⁻² at a drive voltage of 6 V.^[12, 154] This corresponds to a luminous efficiency of 2.5 lm W⁻¹.

Color variations over a wide range of wavelengths have been demonstrated. The bulky isopropyl substituents of 42 cause a blue-shift and green light emission (510 nm), while incorporation of *meta*-linkages, as exemplified by those in 43, results in blue fluorescence. The thiophene group in 44 reduces the HOMO–LUMO energy gap to 1.75 eV (740 nm), and the polymer shows substantial emission in the near infrared region. An ITO/PPV/44/Al device was the first polymer-based IR-emitting LED.^[155] Replacement of both arylene rings with thiophene groups in 45 reduces the energy gap even further to 1.56 eV (800 nm).^[153, 156]

414.

4.2. Other High-Electron-Affinity PPV Derivatives—Electron-Deficient Building Blocks

Apart from CN-PPV, other PPV derivatives with electron-withdrawing substituents, this time on the arylene ring, have been investigated for EL applications (Scheme 14). Poly-



Scheme 14. High-electron-affinity PPV derivatives with electron-withdrawing groups on the aromatic ring.

(phenylene vinylene)s 46 and 47 bearing halide and alkoxy groups on the ring are accessible through the Wessling method.^[157] High molar masses required rigorous purification of the monomers and optimization of the polymerization conditions. We have found that PPV derivatives with bromo (47)^[158] or trifluoromethyl (48) substituents^[159, 160] can be readily obtained by a bromo-precursor route (see Scheme 5) or by Horner–Wittig polycondensation.^[159] Polymer 48 in particular shows higher electron affinities than PPV. The halogen-substituted PPVs 46 and 47 were found to emit red ($\lambda_{\text{max}} = 620–630$ nm) light,^[157] while the trifluoromethyl derivative 48 emits yellow to yellow-orange ($\lambda_{\text{max}} = 540–570$ nm) light. The PL quantum yields for 48 are much lower than for PPV and single-layer devices gave only weak emission, and EL internal efficiencies reached 0.01 % in double-layer devices with PPV as hole-injecting layer and Al as cathode.^[160, 161] In view of their poor PL quantum yields these materials are more likely to prove useful as ECHB than as emissive materials.

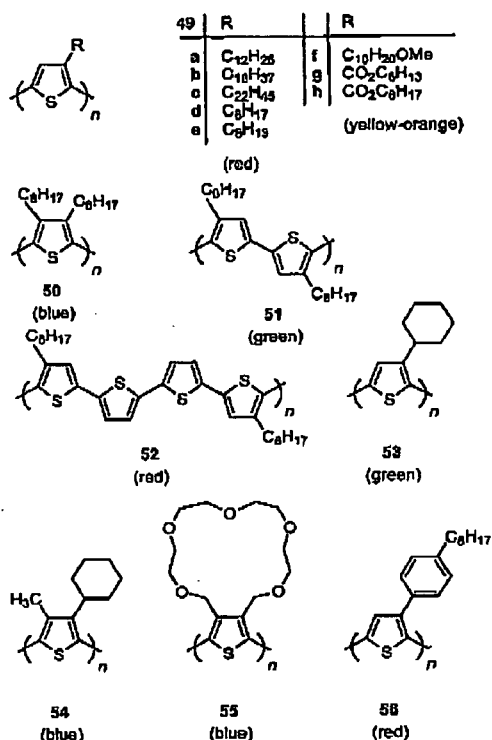
5. Color Tuning—Varying the HOMO–LUMO Gap

A major advantage of polymers as EL materials is the ease with which their structures can be altered, thus enabling the chemist to tune the properties by modifying their structures. In this section we wish to illustrate both the wide range of polymer structures, which can be used for EL purposes, and also to show how the properties, especially the emission color, can be adjusted by varying the aromatic ring, the substituents, and the regioregularity of the conjugated polymer.

5.1. Poly(3-alkylthiophene)s—A Good Red

Poly(3-alkylthiophene)s provide a good example of how the color of emission can be varied in polymer LEDs by modifying both the polymer structure and the design of the devices (Scheme 15). Soluble poly(3-alkylthiophene)s 49 are readily prepared by the polymerization of the corresponding

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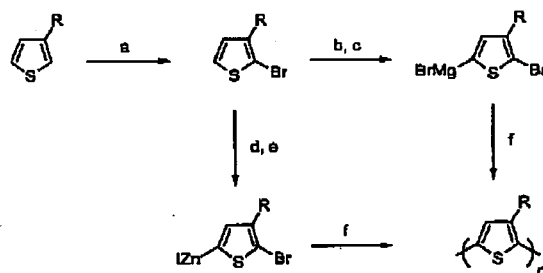
Scheme 15. Poly(alkylthiophene) derivatives and their emission color range.

3-alkylthiophene monomers in the presence of excess ferric chloride,^[162] or by nickel-catalyzed coupling of dihalothiophenes with thiophene-bis(magnesium halide)s.^[163, 164] Red electroluminescence (emission maxima at about 640 nm) from 49a–e, which have alkyl chain lengths varying from 6 to 22 carbon atoms, has been reported by various groups.^[165–169] The emission intensity became larger with increasing chain length, possibly owing to the improved confinement of excitons. Homopolymers based on 3-alkylthiophenes exhibit good red color purity, but they tend to have rather low fluorescence quantum yields. The use of charge carrier confinement layers^[166] or doping with fluorescent dye materials^[170] markedly increases device efficiency. Substitution of the hydrocarbon side chains as in 49f–h^[171, 172] produced a slight blue shift in the emission maximum and gave yellow-orange emission.

The emission frequency depends considerably on the nature and regularity of the side chains on the polymers. Hadziioannou et al.^[173] studied alkylated polythiophenes 50–52 and reported that there was a correlation between their emission maximum and the inverse number of thiophenes between two consecutive head-to-head (2,2'-coupled) dyads. Thus the polymer 50 showed an emission maximum at 460 nm (2.7 eV), while 51 and 52 had emission maxima at 530 (2.35 eV) and 550 nm (2.25 eV), respectively. Similarly, the emission maximum for Holdercroft and Xu's^[174, 175] poly(3-hexylthiophene) (49e) was blue-shifted with increasing

amounts of head-to-head dyads. Similar blue shifts can be obtained by introducing bulky substituents; the cyclohexyl substituted polythiophene 53 has its emission maximum in the green (555 nm).^[176–178] Blue emission can be obtained by substitution at both the 3- and 4-positions as in 54 (460 nm)^[177–179] or 55 (470 nm).^[180] Bilayer devices containing the 4-octylphenyl-substituted poly[α,α' -bithienyl] analogue of 56 and a thick layer of PBD 28 emit white light due to the simultaneous emission of three colors.^[181] The red and green emission can be suppressed in favor of near ultraviolet emission (397 nm) for a device using a blend of the polythiophene 56 and 28 with a further layer of 28 as emissive material.^[134] The blue shifts can be attributed to the twisting of the conjugated backbone out of coplanarity due to the bulky substituents.

Greater control of emission colors requires the ability to control polymer regioregularity. When thiophenes are polymerized with ferric chloride or by Grignard coupling reactions, the resulting polymers are regiorandom, with a preponderance of head-to-tail (2,5'-) coupling, varying from 52 to 80 % according to the method used.^[164] Some control can be obtained in specific cases. For example, coupling of oligomeric alkylthiophenes results in regioregular copolymers,^[173, 182] while polymerization of a 3-arylthiophene with ferric chloride under carefully controlled conditions can give high-molecular-weight, regioregular (94 % head-to-tail) polymers such as 56^[183] because the aryl group preferentially stabilizes the cationic charge in the intermediates at the 2-position. More general routes for the synthesis of regioregular (head-to-tail) poly(3-alkylthiophene)s have been developed by McCullough et al.^[184–187] and Rieke et al.^[188, 189] who utilized nickel-catalyzed coupling of 2-halo-5-metallothiophenes (Scheme 16). These routes require extremely pure monomers for high molecular weights to be produced.



Scheme 16. Routes to regioregular poly(3-alkylthiophene)s: a) Br₂, HOAc, 15 °C; b) LiNPr₂, -40 °C; c) MgBr₂, diethyl ether, -40 °C; d) I₂, HNO₃, CH₂Cl₂; e) Rieke zinc; f) [Ni(Ph₂PCH₂CH₂PPh₂)]Cl₂ or [Ni(Ph₂PCH₂CH(CH₃)PPh₂)]Cl₂.

High regioregularity and a minimum amount of head-to-head dyads greatly influence the color of emission, and it is no surprise that the UV/Vis absorption spectrum of regioregular poly(3-hexylthiophene) (49e) indicates a longer conjugation length than observed for the corresponding regiorandom material.^[190] McCullough et al. found that regioregular 49e also showed a higher EL quantum efficiency than its regiorandom counterpart.^[191] Comparison of regioregular

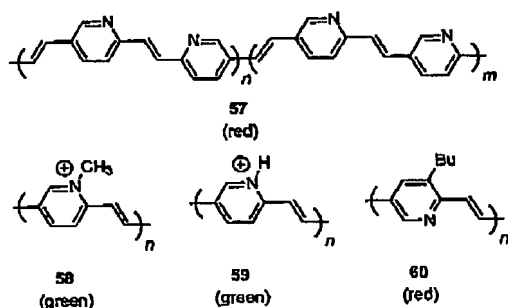
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and regiorandom 49a and 49e prepared by us, however, showed no significant differences in their emission spectra or efficiencies.^[192, 193]

The emissive properties of regioregular statistical copolymers can be tuned by varying the length of the alkyl side chain and the relative ratios of the organometallic monomers.^[186, 194] We have also prepared poly(3-alkylthiophene) copolymers with side chains containing terminal azide groups which have enabled us to cross-link the deposited films so as to produce insoluble materials for use in multilayer devices.^[195] Polarized emission from stretch-oriented polythiophenes has been observed.^[196] An oriented film of poly[3-(10-methoxydecyl)thiophene] (49f) has been deposited by Langmuir-Blodgett techniques and shown to emit polarized electroluminescence.^[197]

5.2. Electron-Deficient Aromatic Rings

Color control by alteration of substituents and regioregularity is also illustrated by the pyridine-based analogue 57 of PPV and its derivatives (Scheme 17). Stille coupling of 2,5-



Scheme 17. Pyridine-based analogues of PPV.

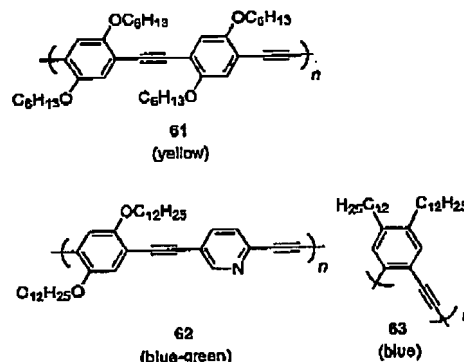
dibromopyridine and 1,2-bis(tributylstannyl)ethylene^[198] gives 57 as an orange powder that is soluble in *m*-cresol. Alkylation and protonation furnish the N-alkylated 58 and N-protonated 59 derivatives, respectively. Both are soluble in chloroform although 58 tends to decompose in the presence of nucleophiles. Coupling of 3-butyl-2,5-dibromopyridine gives the substituted polymer 60,^[199, 200] which is soluble in conventional organic solvents.

The parent polymer 57 has a PL maximum in the red region (590 nm). The C-alkylated polymers 60 exhibit a red-shift to 630 nm, whereas a blue-shift to 540 nm is seen for the N-alkylated polymer 58. Protonated polymer 59 has a more complex spectrum with emission maxima at 535 and 570 nm.

Owing to the lower symmetry of the pyridine ring, polymer 57 can exist in three regioisomeric forms: head-to-tail, head-to-head, and random. Swager et al.^[201] have prepared the regioregular head-to-tail and head-to-head polymers and found that the three isomers show different UV/Vis absorption, PL, and EL emission spectra, with EL emission maxima of 575 nm (random), 584 nm (head-to-tail) and 605 nm (head-to-head).^[202]

5.3. Poly(phenylene ethynylene)s—Stiffening the Polymer Chain

LEDs based on poly(phenylene ethynylene)s such as 61 (the dehydro-analogues of PPVs) are typically prepared by Sonogashira coupling of diethynylbenzenes and dihalobenzenes (Scheme 18).^[203, 204] The synthesis and properties of poly-



Scheme 18. Examples of poly(phenylene ethynylene)s.

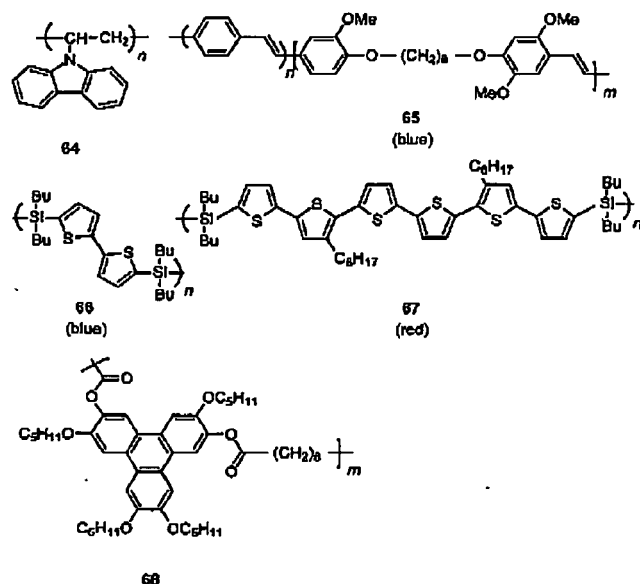
(arylene ethynylene)s have recently been reviewed by Giesse.^[205] Poly(phenylene ethynylene) 61 shows yellow emission with maxima around 600 nm,^[203, 206, 207] whereas the corresponding dialkoxy-PPVs give rise to red or red-orange emission. Incorporation of a 2,5-pyridinediyl unit (62) gives a blue-shift and blue-green emission ($\lambda_{\text{max}} = 480$ nm).^[208] Blue (410 nm) emission is obtained from poly(3,4-dialkyl-1,6-phenylene ethynylene)s 63,^[209] prepared by palladium cross-coupling reaction of a 3,4-dialkyl-1,6-diiodobenzene and a 3,4-dialkyl-1,6-diethynylbenzene. Steric interactions may cause twisting of the polymer chain which reduces the effective conjugation length, but other factors also probably contribute to the overall emission characteristics. The poly(phenylene ethynylene)s have received some attention in the patent literature, but have been generally rather disappointing in EL applications.

5.4. Polymers with Isolated Chromophores—The Best of Both Worlds?

An alternative approach to designing a polymeric EL material is to blend a fluorescent dye in an inert polymer matrix such as polystyrene. Unfortunately, such blends often do not electroluminesce because the volume fraction of the electroactive species is too low. However, if an electroactive polymer such as poly(vinyl carbazole) (PVK) 64 is included, blends with tiny amounts of luminescent material can yield quite bright electroluminescent devices. An extension of this concept is to link the luminescent chromophore covalently to a polymer.

In polymers with isolated chromophores, the color is determined by altering the conjugation length of the chromophore. For example, Klavetter et al.^[210] has prepared copolymers of type 65 by Wittig condensation using varying amounts of a flexible-chain dialdehyde and a bis-yliide

(Scheme 19). The emission peak of **65** ranges from 2.75 eV (460 nm) (blue) to 2.25 eV (550 nm) (yellow-green) depending on the amount of flexible linker content. Thus, the emission color can be easily altered by simply changing the comonomer feed ratio.



Scheme 19. Examples of polymers with isolated chromophores.

Hadziioannou et al. have prepared oligothiophene-dibutylsilane copolymers such as **66** or **67**^[211–214] whose emission maxima range from blue (415 nm) for **66** to red (612 nm) for **67** according to the number of thiophene and silane units. The red-shift produced by increasing the number of silane units is slight and the emission color is mainly determined by the number of thiophene units. At present the advantages of the embedded chromophore polymers over the more traditional fully conjugated materials remain to be demonstrated.

Polymers that have special features of processability in addition to high luminescent properties are particularly attractive. Much can be expected from improving supramolecular order. The recent work of Ringsdorf, Haarer et al. on discotic columnar phases involving triphenylene stacks shows much promise.^[215] For example, the liquid-crystalline polymer **68** incorporating these structural features had a particular tendency to orient parallel to the film surface. Perhaps not surprisingly, this material showed steep current–voltage curves, low threshold fields, and high charge carrier mobilities.^[216–217]

6. Blue Light-Emitting Polymers—The “Holy Grail”

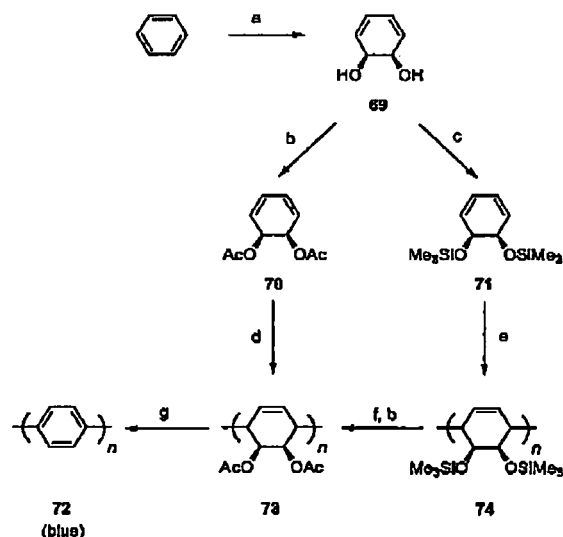
The preceding sections outlined how a wide variety of conjugated electroluminescent polymers gives access to a whole range of emission colors. Multicolor display applications require at least three basic colors: red, green, and blue. Blue EL—already difficult to achieve with inorganic semiconduc-

tors—has been sought in conjugated polymers having a high HOMO–LUMO energy gap, and in copolymers containing high HOMO–LUMO, short conjugated segments. The search for a stable, highly efficient, bright blue light-emitting polymer continues. The following milestones have been passed.

6.1. Poly(*para*-phenylene)s—The Blue Paradigm

The design of blue-emitting electroluminescent polymers based on PPV-type materials with interrupted conjugation (Section 3.1) suffers from the drawback that emission occurs usually from the more conjugated segments, and the emission spectrum is therefore broadened and red-shifted. The alternative use of short, defined PPV oligomers will be discussed in succeeding sections (6.2 and 6.3). High HOMO–LUMO gap polymers are required for blue light emission. The first blue-emitting ($\lambda_{\text{max}} = 470$ nm) polymer LED was made by Yoshino et al.^[218] using poly(9,9-dihexylfluorene) (**75a**) by oxidative coupling of the fluorene monomer with ferric chloride.^[219, 220] This material has a poly(*para*-phenylene) (PPP) backbone, and derivatives of PPP **72** have been the focus of much research into the development of blue-emitting polymers. Higher polyarylenes have been little studied, possibly owing to the difficulties associated with their synthesis.

Leising et al.^[221, 222] were the first to describe the use of PPP **72** as a blue light emitter [$\lambda_{\text{max}} = 459$ nm (2.7 eV)]. Like PPV, unsubstituted PPP is insoluble and not processible. Although films of oligomeric (9–10mer) poly(phenylene)s can be obtained by vacuum deposition,^[223] the preparation of the polymer again requires suitable precursor routes (a topic recently reviewed by Gin and Conticello^[224]). The original synthesis of unsubstituted PPP employs the ICI route based on *cis*-1,2-cyclohexadienediol (**69**) as starting material (Scheme 20).



Scheme 20. Precursor routes to PPP (**72**): a) *Pseudomonas putida*; b) Ac_2O , pyridine; c) Me_3SiCl , DMAF, pyridine; d) azoisobutyronitrile AIBN, 70 °C; e) bis[(η^5 -allyl)(trifluoroacetato)nickel(η)]; f) Bu_4NF , MeOH ; g) 310–340 °C, Ar.

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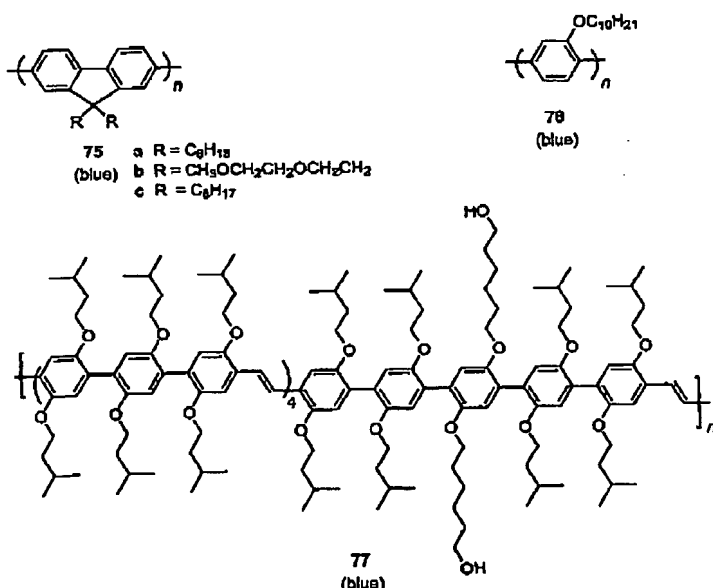
Radical-initiated polymerization of diacetate **70** furnishes the PPP precursor polymer **73**, which suffers from lack of stereoregularity and contains about 15% of 1,2-linkages.^[225, 226] Thermal elimination of acetic acid finally gives the conjugated polymer **72** accompanied by some oligomer formation through chain scission. A number of other diesters have been polymerized by the same method (again with 10–15% of 1,2-linkages in the polymer) and thermally converted to PPP, of which the dimethyl carbonate and dipivaloyl esters yield the polymers with the highest molar masses.^[227] Regioregular PPP is accessible through a nickel-catalyzed stereoregular polymerization of **71**. Despite the regioregularity and low polydispersity of the resulting polymer **74**, there are only limited reports on the electroluminescence of PPP derived from it.

Much interest concentrates also on solution-processible poly(*para*-phenylene)s made soluble by suitable alkyl, aryl, alkoxy, or perfluoroalkyl^[228] solubilizing groups. PPP derivatives with solubilizing alkyl side chains are the most important, and these are available through transition-metal-catalyzed polycondensations (reviewed by Schlüter and Wegner^[229]), especially the Suzuki coupling of arylboronic acids and bromoarenes (optimized by Wegner et al.^[230–232]), and the nickel-catalyzed coupling of substituted dihalobenzenes (reviewed by Yamamoto^[233]), hydroquinone bistriflates,^[234] or bis(mesylates).^[235, 236] Although the degree of polymerization is usually rather limited, the molar masses of the polycondensates are sufficiently high (above 10000 g mol⁻¹) to form robust films for EL applications by spin-coating from solution. Various groups have used the resulting polymeric materials to make blue-emitting LEDs.^[105, 237–242] The best devices so far reported have used the decyloxy derivative **76** (Scheme 21). External efficiencies of up to 3% have been achieved for double layer devices ITO/PVK/76/Ca, and of 0.8% with

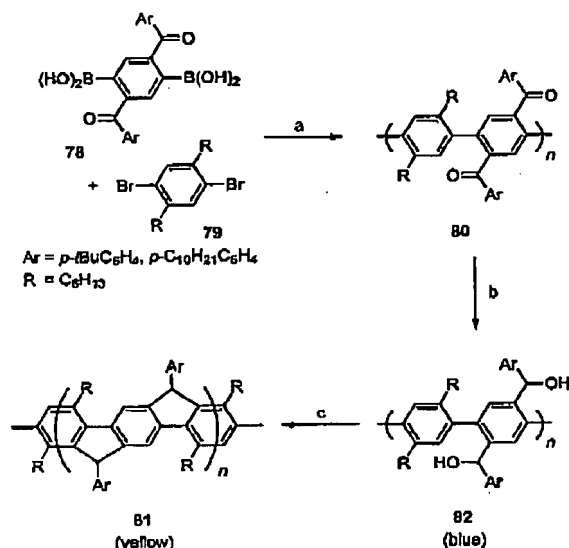
other, more air-stable, metal cathodes.^[240] Polarized emission has been obtained from a device using an oriented Langmuir–Blodgett film of a dialkoxy PPP derivative.^[105] Internal efficiencies of 4% have been measured for blue-emitting (460 nm) devices using the copolymer **77**, containing alternating terphenylene vinylene and quinquephenylene vinylene units, with calcium electrodes.^[243]

The inclusion of solubilizing side groups on the PPP backbone has the drawback that the additional substituents twist the substituted phenylene rings considerably out of plane. This drastically decreases the interaction of the aromatic π -electron system, and an unwanted additional blue-shift in the emission spectrum compared with that for PPP is usually accompanied by a drop in fluorescence quantum yield. The twist cannot occur if the PPP backbone is planarized by incorporation into a ladder polymer. Scherf and Müllen were the first to show that structurally regular ladder-type polymers can be derived from a two-step route in which a soluble poly(*para*-phenylene) is prepared by a Suzuki aryl–aryl coupling of monomers **78** and **79**. After reduction of **80**, the resulting precursor polymer **82** is then subjected to another polymer-analogous intramolecular Friedel–Crafts ring-closing reaction to give **81**. The ladder formation occurs with surprisingly high regularity, and no indications of defects such as cross-linking or incomplete cyclization were found (Scheme 22).^[244, 245] Molar masses of the structurally well-defined, soluble, ladder-type poly(*para*-phenylene)s (LPPPs) **81** are typically up to 20000 g mol⁻¹. The phenylene rings in the ladder polymers are almost planar and the homopolymer shows a broad emission between 650 and 450 nm in the solid state, in contrast to the polymer's sharp fluorescence emission around 450 nm in solution. The large Stokes shift (leading to yellow instead of blue light emission) is especially enhanced after annealing, and has been attributed to the formation of excimers owing to interchain interactions and π -stacking between the planarized conjugated segments.^[246–249]

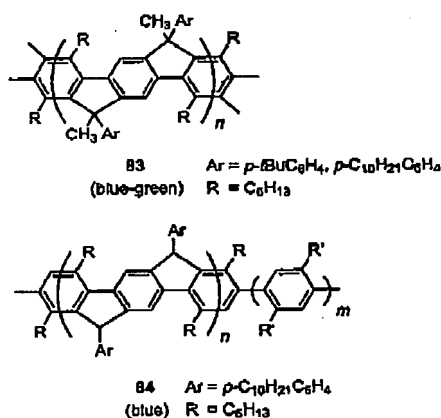
In some cases, blue emission has been observed from LPPP films but it remained unstable over time, again a result of the formation of yellow-emitting aggregates.^[248] Slight structural variations have been suggested to inhibit the aggregation of planarized ladder-PPPs. After introduction of a methyl group at the methine bridge, the resulting ladder polymer **83**^[250] shows stable blue-green emission with external efficiencies of up to 4% (Scheme 23).^[251–253] Even more productive are random interruptions in the conjugated chain. In statistical copolymers **84**, called "step-ladder" copolymers, the conjugated chain is disrupted because the LPPP segments are connected by twisted oligophenylene spacers. These copolymers give stable films which remain blue-emitting even after annealing.^[248] Pure blue emission with 0.1% internal efficiency can also be accomplished by diluting the ladder homopolymer (1–10 weight%) in a poly(vinylcarbazole) **64** hole-transporting poly-



Scheme 21. Examples of soluble PPP derivatives.



Scheme 22. Synthesis of ladder-PPP (81): a) [Pd(PPh₃)₄]; b) LiAlH₄; c) BF₃.



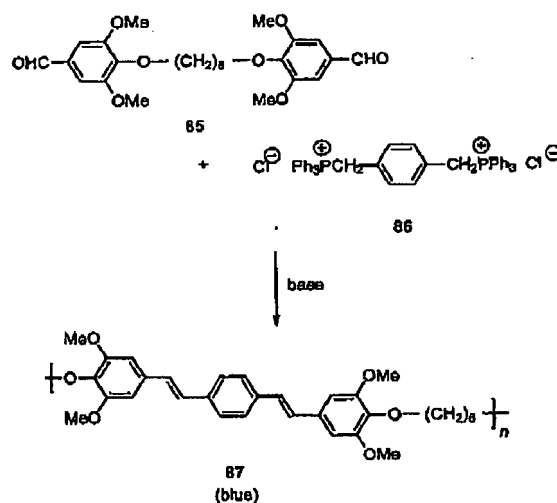
Scheme 23. Examples of blue-emitting, ladder-type PPP derivatives.

mer matrix.^[254] This presumably inhibits aggregation. The above-mentioned poly(9,9-dihexylfluorene) (75a)^[166, 224, 225] has a structure halfway between PPP and LPPP. A similar derivative BDOH-PF (75b) has been prepared by Pei and Yang.^[256] Very little lifetime data is available for these materials as their development is in its infancy. However, the polyfluorene derivative 75c has shown considerable promise in a number of applications.^[257]

6.2. Polymers with Isolated Main-Chain Chromophores—Polycondensates by Wittig Reaction

Since the wavelength of the emitted light is dependent on the conjugation length of the chromophore, lowering this length will result in a blue-shift in the emission. One way to

achieve a blue-emitting polymer, therefore, is to interrupt the conjugation of the polymer at short intervals with nonconjugated segments in between. As was discussed in Section 3.1 above, simple modification of the PPV synthesis gives access to PPV-derived blue light-emitting polymers with a high concentration of a fluorescent chromophore and, at the same time, with a statistical range of short conjugation lengths (see Scheme 8). This method, however, only allows limited control of the conjugation length. Another way to polymers with well-defined fluorescent π -electron systems makes use of a Wittig condensation of an arylene bisphosphonium salt 86 with a bisbenzaldehyde 85 already containing a spacer unit (Scheme 24). This has been used, for example, to make



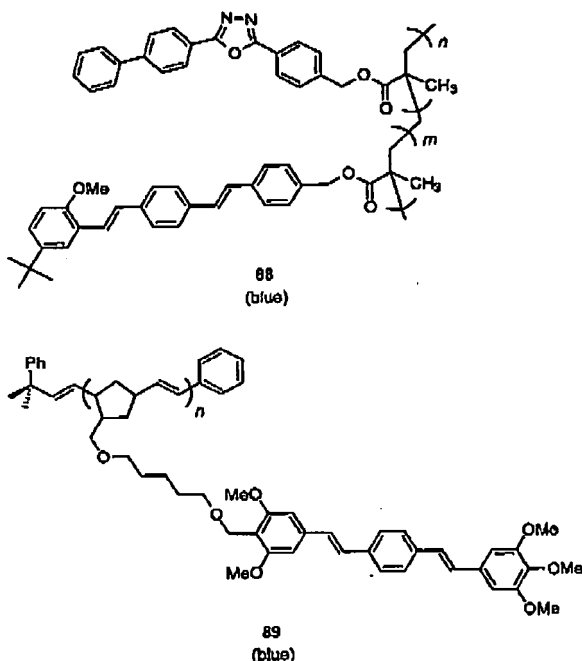
Scheme 24. Synthesis of a blue-emitting copolymers with isolated chromophore by Wittig reaction.

polycondensate 87 in which the oligomeric PPV segments are separated by flexible polymethylene spacers.^[258-260] Such polyethers give blue or blue-green emission ($\lambda_{\text{max}} = 470\text{--}495\text{ nm}$).

6.3. Polymers with Conjugated Side-Chain Chromophores—"Comb" Lumophores

Another approach towards polymers with well-defined chromophores is based on polymers with luminescent conjugated side chains. As the backbone can now be any nonconjugated "standard" polymer, this enables, in principle, utilization of the considerable body of expertise developed in classical polymer synthesis to adjust the physical properties of the polymer. Our own efforts have concentrated on polymethacrylates such as the copolymers 88 bearing diaryloxadiazole charge-transporting and distyrylbenzene emissive units as side chains (Scheme 25).^[74, 134, 141] Bilayer devices with 88 as emissive layer and PPV as hole-transport layer showed blue emission ($\lambda_{\text{max}} = 457\text{ nm}$) (with a tail in the yellow-green region, owing to emission from PPV, and an efficiency of 0.037%). The polymers 88 unfortunately were not very stable,

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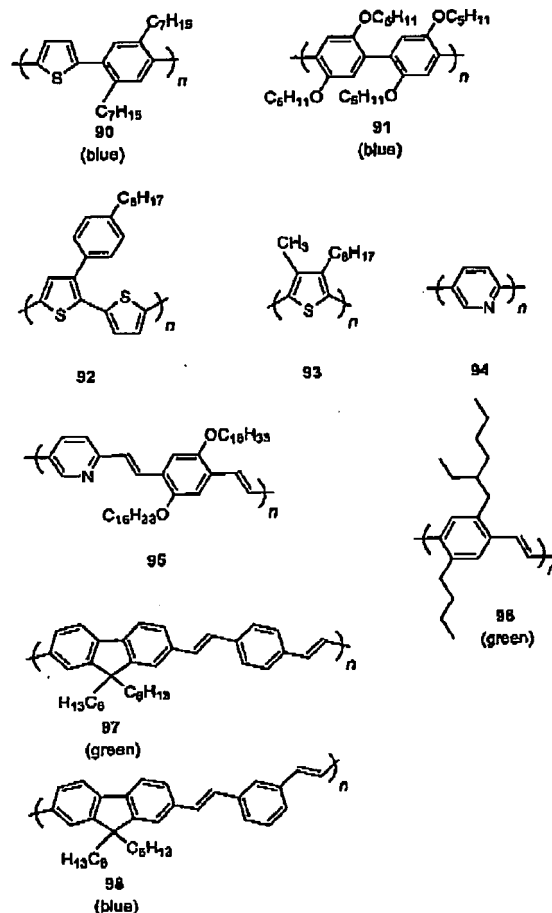
Scheme 25. Examples of electroluminescent polymers with side-chain chromophores.

degrading on storage, photoexcitation, and particularly during device operation. Significant improvements can be obtained by cross-linking.^[141]

Schrock et al.^[243] have used ROMP on a norbornene monomer with a side chain distyrylbenzene chromophore attached to produce polymer 89, which shows blue ($\lambda_{\text{max}} = 475 \text{ nm}$) electroluminescence with 0.3% internal efficiency and a turn-on voltage of 12 V when calcium was the cathode. The efficiency increased to 0.55% for a blend of 89 and an oxadiazole electron-transporting material although the turn-on voltage was also raised considerably.

7. Blends and Combinations of Polymers with Other Materials—A Potpourri of Electroluminescent Materials

Improvements in electroluminescence efficiencies have been made by blending conjugated polymers. For example, Nishino et al.^[244] found that blending the red-emitting polymers MEH-PPV (14) and poly(3-hexylthiophene) (49e) gave an initial increase in LED external efficiency up to a maximum of 1.7% (with a calcium cathode and 1 weight % of 49e), which is twice the efficiency of a device made from pure MEH-PPV and three orders of magnitude higher than for pure 49e. The emission spectra showed that the emitted light came from both polymers. Similarly, Salaneck et al.^[245] have found that blue (2.6 eV, 490 nm) emission from the alternating copolymer 90^[246] was enhanced by blending it with the soluble PPP copolymer 91 (Scheme 26). A ratio of 1:9 for



Scheme 26. Examples of polymers used as blends, in SCALE and in other devices.

90:91 produced the highest external quantum efficiency (1.9%) with a peak emission at 474 nm at a bias field of $6 \times 10^7 \text{ V m}^{-1}$. Polymer 91 (460, 400 nm) as a single-layer ITO/91/Ca device emits two peaks at a bias field of $6 \times 10^7 \text{ V m}^{-1}$ and current density of 0.2 mA mm^{-2} .

Even greater enhancements in emission efficiency arise from blending conjugated polymers with partially conjugated polymers. Shim et al.^[247, 248] found that blends of MEH-PPV (14) and a blue-emitting copolymer [similar to] 87 showed emission largely from 14. The emission maximum was blue-shifted by 20–40 nm from that of MEH-PPV. The best efficiency (Al cathode, 87:14 = 15:1) was nearly 500 times greater than that for a device made from pure MEH-PPV. As blending of MEH-PPV with insulating polymers, for example polystyrene, enhances emission efficiency by a factor of less than 10, dilution effects clearly play only a minor part in the enhancement observed. The higher efficiency of the blend is therefore attributed to the charge-transporting properties of copolymer 87 leading to confinement of charge on MEH-PPV. Promising results with blends of the closely related polymers 97 and 98 offer opportunities for stable blue devices.^[249]

Inganäs et al. have shown that blends of polymers with different emission colors are suitable for devices with variable-color, even white light emission. A blend of the polymers 53, 54, 56, and 92 was used to construct a device in which emission can be tuned from red to green by controlling the applied voltage.^[177, 178, 270] A similar blend of polymers 53, 56, and 93 in PMMA emits white light.^[271] The PMMA acts as an insulating matrix and reduces the degree of exciton transfer between the polymers. Another approach employs a blend of a tristyryl-amine in various host polymers such as the polyester Durel, polynorbornene, and poly(vinyl pyridine). The emission of the chromophore depends in this case strongly on the matrix.^[216]

Devices can be constructed by using combinations of conjugated polymers and nonpolymeric materials. Yoshino et al.^[272, 273] have shown that a device containing a mixture of red-orange-emitting 20b and the green-emitting fluorescent dye tris(8-hydroxyquinolino)aluminum produces a voltage-dependent variable emission of orange to green light. Blending of polythiophene 49e with fluorescent dyes has been found to enhance the EL intensity at constant voltage by a factor of up to 70 with an increase in efficiency at constant luminance of up to 20-fold.^[132, 274] With an oxadiazole dye as dopant, the emission color changed from red-orange to white when the voltage was increased.

8. Recent Advances

8.1. Degradation—Oxygen and Water

The one remaining obstacle to the widespread use of polymer LEDs is that, to date, their lifetimes remain lower than the best devices using inorganic or small-molecule organic compounds, although this gap is rapidly being closed. This is in part a result of the susceptibility of conjugated polymers towards oxidative degradation (a topic which has been recently reviewed by Cumpston, Jensen et al.)^[275, 276] Studies on PPV have shown that photooxidation produces carbonyl defects that quench fluorescence.^[13, 277, 278] Singlet oxygen has been implicated in the cleavage of vinylene groups in MEH-PPV (14) and bis(cholestanyloxy)-PPV (19), leading to ester or aldehyde groups.^[279, 280] A study of PPV-based LEDs^[281] revealed that exposure to air produced a drop in efficiency and an increase in threshold voltage, while degradation of the polymer is one of the primary processes involved in the breakdown of MEH-PPV-based LEDs.^[282, 283] These results suggest that suitable protection from aerial oxidation may be a significant factor in improving the lifetime and efficiency of devices. Improvements in device design or encapsulation offer potential methods for achieving this. It should be noted that electrochemical dissolution of the metal electrodes at the electrode/polymer interface has been reported.^[284] This is thought to lead to electrode failure due to corrosion.

8.2. Light-Emitting Electrochemical Cells—Lowering the Barrier to Charge Injection

A potentially significant new advance in the development of electroluminescent devices based on conjugated polymers

has been the discovery^[285–289] of light-emitting electrochemical cells (LECs) in which a conjugated polymer is blended with poly(ethylene oxide), a well-known ion-transporting polymer, and lithium trifluoromethanesulfonate as solid electrolyte. Application of a voltage above the bandgap energy (E_g/e), where e is the electron charge, results in p - and n -doping of regions adjacent to the anode and cathode respectively. A p - n junction is formed within the active layer, and positive and negative charge carriers combine with emission of a photon within the compensated p - n junction.^[22]

With MEH-PPV (14) light emission is observed at a voltage <2.5 V, with external efficiencies of up to 2%. Green emission with a luminance of 100 cdm^{-2} and an external quantum efficiency of 0.4% at a driving voltage of 4 V has been obtained from a device using PPV. Blue-green emission occurs when a soluble poly[9,9-bis(alkyl)fluorene] (BDOH-PF) (75b) serves as emitting polymer. Incorporation of the methoxyethoxyethyl substituents avoids the need for a two-phase blend with an extra ion-supporting polymer.^[256] LECs have a high EL power efficiency, low operating voltages and allow the use of air-stable electrodes. A two-color LEC based on PPV and MEH-PPV has been made in which the emission color can be varied from red to green by altering the applied voltage.^[290, 291] Some serious obstacles, still to be overcome in commercial realization of these devices, are the slow charging time (LECs are electrochemical batteries) and lifetimes under continuous operation, although promising results concerning these issues have been reported.^[292, 293]

8.3. SCALE Devices—Using Alternating Current

Another new advance in device design has been the invention by Epstein and MacDiarmid et al.^[294–300] of symmetrically configured, alternating current, light-emitting (SCALE) devices, which have the typical structure electrode/"insulating" polymer/emissive polymer/"insulating" polymer/electrode. The emissive layers used to date have been polypyridine 94 for blue and copolymer 95 for red light emission. Undoped (emeraldine base) polyaniline and polythiophene 49e are typical "insulating" or electrode-modifying, nonemitting polymers for this type of device.

Use of 49e with 95 as emissive layer gave a device in which the emission color varied depending on whether forward (590 nm) or reverse (635 nm) bias was applied. This is probably caused by charge recombination occurring at different interfaces in the two modes. With polyaniline, the EL spectra were essentially identical in both bias modes with a maximum at 635 nm. As with standard LEDs, one of the electrodes has to be transparent (ITO on glass), while air-stable metals such as Al, Cu, or Au have been used as the other electrode but, unlike standard LEDs, the two electrodes need not have dissimilar work-functions. Turn-on voltages are reported to be lower than those for the corresponding ITO/polymer/metal devices. Operation in alternating current mode also allows ion migration effects to be minimized. These devices remain to be developed to their full potential.

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8.4. Lasers and Microcavities—Stimulated Emission and Superradiance

One method for the enhancement of emission in LEDs makes use of a microcavity structure in which the electroluminescent polymer is sandwiched between two planar, highly reflecting mirrors. When the polymer film thickness is of the order of the wavelength of the emitted light, the device acts as a resonator for a standing electromagnetic wave and produces a marked narrowing in the emission spectrum.^[301–308] A microcavity device has been constructed by using ladder-type PPP 81 in which the emission color can be tuned from red to blue by altering the thickness of the polymer layer.^[307]

Another microcavity device that uses PPV (6) as emissive layer has shown lasing activity with optical pumping, thus presenting the prospect of organic polymer-based lasers.^[309] Similar optically pumped lasing and superradiance effects have been seen with other conjugated polymers.^[309–317] Some investigators have questioned whether or not conjugated polymers will be capable of sustaining the high current densities necessary to realize electrically pumped lasing. The recent work by Bradley and Seidler and colleagues has shown that PPV films emitted light when a scanning tunnelling microscope was used to inject charge at high current densities.^[318]

9. Conclusion and Outlook

The prospects for the success of conjugated polymer-based LEDs as commercially viable display devices depend not only on the development of new materials, but also on progress in the design of devices. The three main factors (other than cost) that will determine the utility of polymer LEDs as light sources are their efficiencies (which control brightness for a given current), threshold or turn-on voltages (which affect power consumption), and lifetimes (over 10 000 h are necessary for many commercial applications). With the appropriate choice of polymer and device design, external efficiencies of up to 4 % can be obtained, which are comparable with the best EL devices based on inorganic or small molecule organic materials, and even much lower values suffice to give emission that is visible under ambient lighting. Turn-on voltages of 5 V or below have also been achieved by the use of charge-transporting layers, enabling devices to be run from low-power sources such as batteries.

The current best results for green materials (Table 2) are from Cambridge Display Technology with two-layer devices based on PPV (550 nm) prepared from a polyelectrolyte precursor copolymer as the emissive layer.^[107] Photoluminescence efficiencies of about 50–80 % have been reported for this material. Luminance efficiencies in excess of 2 lm W⁻¹ and brightnesses in excess of 600 cd m⁻² at 4 V and lifetimes of >1400 h at about 100 cd m⁻² are now achievable. Another promising green polymer is the organic solvent-processible silylated DMOS-PPV (18) for which a respectable 0.1 % external efficiency in a single-layer device with an Al cathode has been reported.^[114, 319]

Table 2. Summary of promising light-emitting polymers across the range of the visible spectrum.

Polymer	Color(λ_{max} [nm])	Efficiency [%] ^[a]
MEH-PPV 14 ^[97]	red-orange (610)	2–4
OC ₆ C ₁₀ -PPV 17 ^[17]	red-orange (610)	2.1 ^[b]
CN-PPV 40 ^[24, 108]	red (710)	0.87
MEH-CN-PPV 41 ^[24]	red-orange (600)	5.0
Polythiophene 49 ^[19, 1]	red (662)	3.85 × 10 ⁻⁴ ^[a]
PPV 6 ^[101]	green (550)	0.3 ^[d]
DMOS-PPV 18 ^[115]	green (500)	0.1 ^[b]
BUEH-PPV 96 ^[122]	green (554)	3.2
BDOH-PPV 75b ^[120]	blue-green (450)	0.3 ^[b]
PPP 72 ^[222]	blue (459)	0.01 ^[b]
Blend 90:91 (1:10) ^[321]	blue (400–490)	2
DO-PPP 76 ^[120]	blue (440)	3
m-LPPP 83 ^[122]	blue-green (491)	0.1 ^[b]
P3V/PSV 77 ^[123]	blue (460)	4 ^[b]

[a] Unless otherwise indicated most devices are two-layer devices with a hole injecting layer between anode and emissive polymer. [b] Signifies single-layer device. [c] Estimated from the published data for a PPV device giving a luminous efficiency 1 lm W⁻¹ at 4 V.

Exciting results for red emitters have emerged from three laboratories, all using closely related solvent-processible oxygenated PPV analogues. At UNLAX, MEH-PPV (14) (λ_{max} = 610 nm) in the configuration ITO/PANI-camphor sulfonate/MEH-PPV/Ca exhibited brightnesses of 100 cd m⁻² at 2.4 V, 4000 cd m⁻² at 4 V, and over 10 000 cd m⁻² at higher voltages. The external quantum efficiency was 2–2.5 % and the luminous efficiency corresponded to 3–4.5 lm W⁻¹. Operating lifetimes in excess of 2000 h at 400–500 cd m⁻² initial brightness were reported.^[97] Two European companies, Philips and Hoechst, have achieved comparable results with OC₆C₁₀-PPV (17).^[17] Philips reported an external quantum efficiency of 2.1 % in the device configuration ITO/17/Ca.^[92, 320] Luminous efficiencies up to 7 lm W⁻¹ and lifetimes of several thousand hours at 100 cd m⁻² were realized. Hoechst fabricated a flexible device based on a dialkoxy-PPV (probably OC₆C₁₀-PPV 17) in the configuration PET-ITO/polymer/Ca, which demonstrated an external efficiency of 2.1 %, a luminous efficiency of 2 lm W⁻¹, and a luminance of 100 cd m⁻² at 3.4 V with a current density of 4.5 mA cm⁻².^[17] Calculations based on the data reported by the Cambridge group show that MEH-CN-PPV (41) has a luminous efficiency of 5 lm W⁻¹.^[123]

Some of the most interesting blue materials are based on polyphenylene and polyfluorene derivatives, but the major progress has been largely from academic laboratories, and serious industrial evaluation has still to be carried out. One of the best results has been obtained with the poly(2-decyloxy-1,4-phenylene) (76) (λ_{max} = 440 nm), which showed 1.8 % external quantum efficiency in the single-layer device configuration ITO/76/Ca. Problems with polymer film quality were circumvented by using a second PVK buffer and hole injection layer. The two-layer device was more efficient (3 %) and turned on at 15 V to reach a brightness of 490 cd m⁻² at about 30 V.^[240] The blends of copolymers 90 and 91 have already been mentioned as emitting blue light with external efficiency of about 2 %.^[321] The results highlight the general problem for blue emitters that the threshold

voltage is not far removed from that which induces dielectric breakdown. This makes the problem of obtaining good lifetime data considerable. These reservations should be qualified in the light of the recently reported stable devices made from the polyfluorenes 75b and 75c.^[256, 257]

During the past seven years, a wide range of electroluminescent conjugated polymers and copolymers have been made that are suitable for use in LEDs. Alteration of their chemical structures by synthetic design has stimulated the preparation of polymer-based devices emitting in any part of the visible spectrum, and also in the near infrared. By the use of precursor methods thin films of insoluble and intractable materials can be produced. In view of the recent advances in polymer LEDs, efficiencies are now comparable with inorganic or dye-based devices, and ongoing work into improvement of device lifetimes makes the future for these devices promising.

A number of tasks still remain to be performed before the apparent bright prospects of conjugated EL polymers can be realized. Of the wide variety of polymers that have become available in the last seven years, only a few have been extensively studied, and the best materials have yet to be identified. The study of polymer EL devices is an interdisciplinary research area, combining semiconductor physics, polymer chemistry, and materials chemistry, and challenging tasks remain in all of these fields. Although much is known about simple device structures and common electrode materials, devices have yet to be optimized. We also need improved methods (which includes making the polymers more eco-friendly) for the preparation and purification of EL polymers. High purity polymers are required, and the challenge in polymer synthesis is to meet these requirements. High molar masses are advantageous for ensuring good film-forming properties. The long-term stability of polymers and polymer blends during storage and especially in the high electric fields found in operating devices also need to be improved. It will furthermore be necessary to develop suitable encapsulations for the protection of polymers and electrodes from environmental degradative influences. These challenges imply continuing scope for exciting and innovative research into the preparation and application of conjugated electroluminescent polymers. We are confident that markets will emerge for commercial polymer LED devices having a low information content – such as for mobile telephone displays, alphanumeric and backlit LCDs. While the horizon for high information content applications (such as flat-screen color TV) is still several years away, we expect that polymer LEDs will ultimately have a significant input in this area as well.

Appendix: List of Abbreviations

BDOH-PF	poly[9,9-bis(methoxyethoxyethyl)fluorene] 75b
BUEH-PPV	poly[2-(2'-ethylhexyl)-5-butyl-1,4-phenylene vinylene] 96
CN-PPV	poly[2,5-bis(hexyloxy)-1,4-phenylene-(1-cyanovinylene)] 40
DMOS-PPV	poly[2-(dimethyloctylsilyl)-1,4-phenylene vinylene] 18

DO-PPP	poly(2-decyloxy-1,4-phenylene) 76
ECHB	electron-conducting/hole-blocking
EL	electroluminescence
HOMO	highest occupied molecular orbital
ITO	indium-tin oxide
LCD	liquid crystal display
LEC	light-emitting electrochemical cell
LED	light-emitting diode
LPPP	ladder-type poly(<i>para</i> -phenylene)
LUMO	lowest unoccupied molecular orbital
MEH-CN-PPV	poly[2-(2'-ethylhexyloxy)-5-methoxy-1,4-phenylene-(1-cyanovinylene)] 41
MEH-PPV	poly[2-(2'-ethylhexyloxy)-5-methoxy-1,4-phenylene vinylene] 14
OC ₁ C ₁₀ -PPV	poly[2-(3,7-dimethyloctyloxy)-5-methoxy-1,4-phenylene vinylene] 17
P3V/P5V	copolymer 77
PANI	polyaniline
PBD	2-(4-biphenyl)-5-(4- <i>tert</i> -butylphenyl)-1,3,4-oxadiazole 28
PDAF	poly(dialkylfluorene)
PET	poly(ethylene terephthalate)
PL	photoluminescence (fluorescence)
PMMA	poly(methyl methacrylate)
PPP	poly(<i>para</i> -phenylene) 72
PPV	poly(<i>para</i> -phenylene vinylene) 6
ROMP	ring-opening metathesis polymerization
SCALE	symmetrically configured, alternating current, light-emitting (diode)

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- [1] J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. MacKay, R. H. Friend, P. L. Burn, A. B. Holmes, *Nature* 1990, 347, 539–541.
- [2] P. May, *Phys. World* 1995, 8(3), 52–57.
- [3] C. W. Tang, S. A. Van Slyke, *Appl. Phys. Lett.* 1987, 51, 913–915.
- [4] C. Adachi, S. Tokito, T. Tsutsui, S. Saito, *Jpn. J. Appl. Phys.* 1988, 28, L269–L271.
- [5] R. F. Service, *Science* 1996, 273, 878–880.
- [6] H. Nakada, T. Tohma, *Inorganic and Organic Electroluminescence*, Wissenschaft-und-Technik-Verlag, Berlin, 1996, pp. 385–390.
- [7] A. O. Patil, A. J. Heeger, F. Wudl, *Chem. Rev.* 1988, 88, 183–200.
- [8] R. H. Friend, D. D. C. Bradley, A. B. Holmes, *Phys. World* 1992, 5 (11), 42–46.
- [9] D. Bradley, *Curr. Opin. Solid State Mater. Sci.* 1996, 1, 789–797.
- [10] A. B. Holmes, D. D. C. Bradley, A. R. Brown, P. L. Burn, J. H. Burroughes, R. H. Friend, N. C. Greenham, R. W. Gymer, D. A.

REVIEWS

- Halliday, R. W. Jackson, A. Kraft, J. H. F. Martens, K. Pichler, L. D. W. Samuel, *Synth. Met.* 1993, 141, (March 5th 57, 4031–4040.
- [11] K. C. Fox, *New Sci.* 1994, 141, (March 5th), 33–37.
 - [12] D. R. Baigent, N. C. Greenham, J. Grüner, R. N. Marks, R. H. Friend, S. C. Moratti, A. B. Holmes, *Synth. Met.* 1994, 67, 3–10.
 - [13] P. Yam, *Sci. Am.* 1993, 273, (1), 74–79.
 - [14] N. C. Greenham, R. H. Friend, *Solid State Phys.* 1995, 49, 1–149.
 - [15] R. W. Gymer, *Endeavour* 1996, 20, 115–120.
 - [16] L. J. Rothberg, A. J. Lovinger, *J. Mater. Res.* 1996, 11, 3174–3187.
 - [17] J. Salbeck, *Ber. Bunsenges. Phys. Chem.* 1996, 100, 1666–1677.
 - [18] W. R. Salaneck, S. Stafström, J.-L. Brédas, *Conjugated Polymer Surfaces and Interfaces*, Cambridge University Press, Cambridge, 1996.
 - [19] J. R. Sheats, H. Antoniadis, M. Hueschen, W. Leonard, J. Miller, R. Moon, D. Roitman, A. Stocking, *Science* 1996, 273, 884–888.
 - [20] A. J. Lovinger, L. J. Rothberg, *J. Mater. Res.* 1996, 11, 1581–1592.
 - [21] W. J. Feast, I. Tsiouklis, K. L. Pouwer, L. Groenendaal, B. W. Meijer, *Polymer* 1996, 37, 5017–5047.
 - [22] Y. Yang, *MRS Bull.* 1997, 22(6), 31–38.
 - [23] R. H. Friend, G. J. Denton, I. J. M. Hall, N. T. Harrison, A. B. Holmes, A. Köhler, A. Lux, S. C. Moratti, K. Pichler, N. Tessler, C. Towns, *Synth. Met.* 1997, 84, 463–470.
 - [24] M. A. Díaz-García, F. Hida, B. J. Schwartz, M. R. Andersson, Q. Pei, A. J. Heeger, *Synth. Met.* 1997, 84, 455–462.
 - [25] R. A. Wessling, R. G. Zimmerman (Dow Chemical), US-B 3401152, 1968 [*Chem. Abstr.* 1968, 69, 87735a].
 - [26] R. A. Wessling, *J. Polym. Sci. Polym. Symp.* 1985, 72, 55–66.
 - [27] R. W. Lenz, C.-C. Han, J. Stenger-Smith, R. B. Karasz, *J. Polym. Sci. Polym. Chem.* 1988, 26, 3241–3249.
 - [28] P. L. Burn, D. D. C. Bradley, R. H. Friend, D. A. Halliday, A. B. Holmes, R. W. Jackson, A. Kraft, *J. Chem. Soc. Perkin Trans. 1* 1992, 3225–3231.
 - [29] R. O. Garay, U. Baier, C. Buback, K. Müllen, *Adv. Mater.* 1993, 5, 561–564.
 - [30] F. R. Denton, P. M. Lahti, F. E. Karasz, *J. Polym. Sci. Polym. Chem.* 1992, 30, 2223–2231.
 - [31] D. A. Halliday, P. L. Burn, R. H. Friend, D. D. C. Bradley, A. B. Holmes, *Synth. Met.* 1993, 55, 902–907.
 - [32] F. Papadimitrakopoulos, K. Konstantinidis, T. M. Miller, R. Opila, B. A. Chandross, M. E. Galvin, *Chem. Mater.* 1994, 6, 1563–1568.
 - [33] F. Papadimitrakopoulos, M. Yan, L. J. Rothberg, H. E. Katz, E. A. Chandross, M. E. Galvin, *Mol. Cryst. Liq. Cryst.* 1994, 256, 663–669.
 - [34] V. H. Tran, V. Massardier, T. P. Nguyen, J. Davaas, *Polymer* 1996, 37, 2061–2065.
 - [35] H. H. Kim, R. G. Swartz, Y. Ota, T. K. Woodward, M. D. Feuer, W. L. Wilson, *J. Lightwave Technol.* 1994, 12, 2114–2120.
 - [36] M. Herold, J. Gmeiner, M. Schwoerer, *Acta Polym.* 1994, 45, 392–395.
 - [37] M. Herold, J. Gmeiner, W. Riess, M. Schwoerer, *Synth. Met.* 1996, 76, 109–112.
 - [38] A. Beerden, D. Vanderzande, J. Gelan, *Synth. Met.* 1992, 52, 387–394.
 - [39] Y. Nishikata, M. Kakimoto, Y. Imai, *Thin Solid Films* 1989, 179, 191–197.
 - [40] A. Wu, M. Jikei, M. Kakimoto, Y. Imai, S. Uchiyama, Y. Takahashi, *Chem. Lett.* 1994, 2319–2322.
 - [41] J. H. Kim, Y. K. Kim, B. C. Sohn, D.-Y. Keng, J.-I. Jin, C.-H. Kim, C.-H. Pyun, *Synth. Met.* 1995, 71, 2023–2024.
 - [42] A. Wu, M. Kakimoto, *Adv. Mater.* 1995, 7, 812–814.
 - [43] A. Wu, M. Jikei, M. Kakimoto, Y. Imai, S. Uchiyama, Y. Takahashi, *Mol. Cryst. Liq. Cryst.* 1995, 267, 441–446.
 - [44] R. C. Smith, W. M. Fischer, D. L. Gin, *J. Am. Chem. Soc.* 1997, 119, 4092–4093.
 - [45] F. Louwet, D. Vanderzande, J. Gelan, *Synth. Met.* 1992, 52, 125–130.
 - [46] F. Louwet, D. Vanderzande, J. Gelan, *Synth. Met.* 1995, 69, 509–510.
 - [47] F. Louwet, D. Vanderzande, J. Gelan, J. Mullens, *Macromolecules* 1995, 28, 1330–1331.
 - [48] S. Son, A. J. Lovinger, M. E. Galvin, *Polym. Mater. Sci. Eng.* 1995, 72, 567–568.
 - [49] E. G. J. Staring, D. Braun, G. L. J. A. Rikken, R. J. C. E. Demandt, Y. A. R. R. Kessener, M. Bouwman, D. Broer, *Synth. Met.* 1994, 67, 71–75.
 - [50] S. Iwatsuki, M. Kubo, T. Kumeuchi, *Chem. Lett.* 1991, 1971–1974.
 - [51] O. Schiffer, A. Greiner, J. Pommerhne, W. Guss, H. Vestweber, H. Y. Tak, H. Bässler, C. Schmidt, G. Lüsser, B. Schartel, V. Stämpfl, J. H. Wendorff, S. Spiegel, C. Möller, H. W. Spiess, *Synth. Met.* 1996, 82, 1–9.
 - [52] W.-P. Chang, W.-T. Whang, P.-W. Lin, *Polymer* 1996, 37, 1513–1518.
 - [53] Y.-J. Miao, G. C. Bazan, *J. Am. Chem. Soc.* 1994, 116, 9379–9380.
 - [54] V. P. Conticello, D. L. Gin, R. H. Grubbs, *J. Am. Chem. Soc.* 1992, 114, 9708–9710.
 - [55] N. C. Greenham, R. H. Friend, D. D. C. Bradley, *Adv. Mater.* 1994, 6, 491–494.
 - [56] H. Becker, S. E. Burns, R. H. Friend, *Phys. Rev. B* 1997, 56, 1893–1905.
 - [57] P. L. Burn, A. B. Holmes, A. Kraft, A. R. Brown, D. D. C. Bradley, R. H. Friend, *Mater. Res. Soc. Symp. Proc.* 1992, 247, 647–654.
 - [58] N. C. Greenham, R. H. Friend, A. R. Brown, D. D. C. Bradley, K. Pichler, P. L. Burn, A. Kraft, A. B. Holmes, *Proc. SPIE Int. Soc. Opt. Eng.* 1993, 1910, 84–91.
 - [59] I. A. Hümmelgen, Y. D. Yadava, L. S. Roman, A. C. Arias, M. R. Fernandez, F. C. Nart, *Bull. Mater. Sci.* 1996, 19, 423–427.
 - [60] M. Meier, M. Cölle, S. Karg, E. Buchwald, J. Gmeiner, W. Riess, M. Schwoerer, *Mol. Cryst. Liq. Cryst.* 1996, 283, 197–202.
 - [61] A. C. Fou, O. Onitsuka, M. Ferreira, D. Howie, M. F. Rubner, *Polym. Mater. Sci. Eng.* 1995, 72, 160–161.
 - [62] A. C. Fou, O. Onitsuka, M. Ferreira, M. F. Rubner, B. R. Hsieh, *Mater. Res. Soc. Symp. Proc.* 1995, 369, 575–580.
 - [63] M. Onoda, K. Yoshino, *Jpn. J. Appl. Phys.* 1995, 34, L260–L263.
 - [64] M. Onoda, K. Yoshino, *J. Appl. Phys.* 1995, 78, 4456–4462.
 - [65] A. C. Fou, O. Onitsuka, M. Ferreira, M. F. Rubner, B. R. Hsieh, *J. Appl. Phys.* 1996, 79, 7501–7509.
 - [66] M. Ferreira, O. Onitsuka, A. C. Fou, B. Hsieh, M. F. Rubner, *Mater. Res. Soc. Symp. Proc.* 1996, 413, 49–54.
 - [67] D. Yoo, A. Wu, J. Lee, M. F. Rubner, *Synth. Met.* 1997, 85, 1425–1426.
 - [68] A. R. Brown, D. D. C. Bradley, J. H. Burroughes, R. H. Friend, N. C. Greenham, P. L. Burn, A. B. Holmes, A. Kraft, *Appl. Phys. Lett.* 1992, 61, 2793–2795.
 - [69] M. Strukelj, F. Papadimitrakopoulos, T. M. Miller, L. J. Rothberg, *Science* 1995, 267, 1969–1972.
 - [70] Y. Yang, Q. Pei, *J. Appl. Phys.* 1995, 77, 4807–4809.
 - [71] X.-C. Li, M. Giles, J. Grüner, R. H. Friend, A. B. Holmes, S. C. Moratti, *Polym. Mater. Sci. Eng.* 1995, 72, 463–464.
 - [72] E. Buchwald, M. Meier, S. Karg, P. Pösch, H.-W. Schmidt, P. Strohiegl, W. Riess, M. Schwoerer, *Adv. Mater.* 1995, 7, 839–842.
 - [73] X.-C. Li, A. B. Holmes, A. Kraft, S. C. Moratti, G. C. W. Spencer, F. Cacialli, J. Grüner, R. H. Friend, *J. Chem. Soc. Chem. Commun.* 1995, 2211–2212.
 - [74] X.-C. Li, F. Cacialli, M. Giles, J. Grüner, R. H. Friend, A. B. Holmes, S. C. Moratti, T. M. Yong, *Adv. Mater.* 1995, 7, 898–900.
 - [75] X.-C. Li, G. C. W. Spencer, A. B. Holmes, S. C. Moratti, F. Cacialli, R. H. Friend, *Synth. Met.* 1996, 76, 153–156.
 - [76] M. Strukelj, T. M. Miller, F. Papadimitrakopoulos, S. Son, *J. Am. Chem. Soc.* 1995, 117, 11976–11983.
 - [77] M. Meier, E. Buchwald, S. Karg, P. Pösch, M. Greczmiel, P. Strohiegl, W. Riess, *Synth. Met.* 1996, 76, 95–99.
 - [78] S. Doi, M. Kurabara, T. Noguchi, T. Ohnishi, *Synth. Met.* 1993, 57, 4174–4179.
 - [79] D. Braun, A. J. Heeger, *Appl. Phys. Lett.* 1991, 58, 1982–1984.
 - [80] D. Braun, A. J. Heeger, H. Kroemer, *J. Electron. Mater.* 1991, 20, 945–948.
 - [81] A. R. Brown, N. C. Greenham, J. H. Burroughes, D. D. C. Bradley, R. H. Friend, P. L. Burn, A. Kraft, A. B. Holmes, *Chem. Phys. Lett.* 1992, 200, 46–54.
 - [82] N. C. Greenham, A. R. Brown, J. H. Burroughes, D. D. C. Bradley, R. H. Friend, P. L. Burn, A. Kraft, A. B. Holmes, *Proc. SPIE Int. Soc. Opt. Eng.* 1993, 1910, 111–119.
 - [83] G. Gustafsson, Y. Cao, G. M. Treacy, P. Klavetter, N. Colaneri, A. J. Heeger, *Nature* 1992, 357, 477–479.
 - [84] A. J. Heeger, D. Braun (UNLAX), WO-B 92/16023, 1992 [*Chem. Abstr.* 1993, 118, 157401j].
 - [85] G. I. Sarnecki, P. L. Burn, A. Kraft, R. H. Friend, A. B. Holmes, *Synth. Met.* 1993, 55, 914–917.

- [86] R. Wudl, R.M. Allemand, G. Srdanov, Z. Ni, D. McBranch, *ACS Symp. Ser.* 1991, 455; R. Wudl (University of California), US-B 5189136, 1990 [*Chem. Abstr.* 1993, 118, 255575p].
- [87] D. Braun, E. G. J. Staring, R. C. J. E. Demandt, G. L. J. Rikken, Y. A. R. R. Kessener, A. H. J. Vanhulzen, *Synth. Met.* 1994, 66, 75-79.
- [88] I. Murase, T. Ohnishi, T. Noguchi, M. Hirooka, *Synth. Met.* 1987, 17, 639-644.
- [89] S. A. Askari, S. D. Rughooputh, F. Wudl, *Synth. Met.* 1989, 29, E129-E134.
- [90] D. A. Halliday, D. D. C. Bradley, P. L. Burn, R. H. Friend, A. B. Holmes, *Synth. Met.* 1991, 41, 931-934.
- [91] H. G. Gilch, W. L. Wheelwright, *J. Polym. Sci. A1* 1966, 4, 1337-1349.
- [92] W. J. Swatos, B. Gordon, *Polym. Prepr.* 1990, 31, 505-506.
- [93] I. D. Parker, *J. Appl. Phys.* 1994, 75, 1656-1666.
- [94] Y.-E. Kim, H. Park, J.-J. Kim, *Appl. Phys. Lett.* 1996, 69, 599-601.
- [95] I. D. Parker, H. H. Kim, *Appl. Phys. Lett.* 1994, 64, 1774-1776.
- [96] H. H. Kim, T. M. Miller, B. H. Westerwick, Y. O. Kim, E. W. Kwock, M. D. Morris, M. Cerullo, *J. Lightwave Technol.* 1994, 12, 2107-2113.
- [97] G. Yu, *Synth. Met.* 1996, 80, 143-150.
- [98] G. Gustafsson, G. M. Treacy, Y. Cao, F. Klavetter, N. Colaneri, A. J. Heeger, *Synth. Met.* 1993, 57, 4123-4127.
- [99] E. Westerweel, P. Smith, A. J. Heeger, *Adv. Mater.* 1995, 7, 788-790.
- [100] S. A. Carter, M. Angelopoulos, S. Karg, P. I. Brock, J. C. Scott, *Appl. Phys. Lett.* 1997, 70, 2067-2069.
- [101] J. C. Carter, I. Grizzell, S. K. Heeks, D. J. Lacey, S. G. Latham, P. G. May, O. R. de los Paños, K. Pichler, C. R. Towns, H. F. Wittmann, *Appl. Phys. Lett.* 1997, 71, 34-36.
- [102] T. W. Hagler, K. Pakbaz, J. Moulton, F. Wudl, P. Smith, A. J. Heeger, *Polymer* 1991, 32, 339-342.
- [103] T. W. Hagler, K. Pakbaz, K. R. Vosa, A. J. Heeger, *Phys. Rev. B* 1991, 44, 8652-8666.
- [104] M. Hamaguchi, K. Yoshino, *Appl. Phys. Lett.* 1995, 67, 3381-3383.
- [105] V. Cimrová, M. Rammes, D. Neher, G. Wegner, *Adv. Mater.* 1996, 8, 146-149.
- [106] F. Wudl, S. Höger, C. Zhang, K. Pakbaz, A. J. Heeger, *Polym. Prepr.* 1993, 34, 197-198.
- [107] N. N. Barashkov, D. J. Guerrero, H. J. Olivos, J. P. Ferraris, *Synth. Met.* 1995, 75, 153-160.
- [108] B. R. Hsieh, H. Antoniadis, D. C. Bland, W. A. Feld, *Adv. Mater.* 1995, 7, 36-38.
- [109] C. Zhang, H. von Seggern, K. Pakbaz, F. Wudl, A. J. Heeger, *J. Electron. Mater.* 1993, 22, 413-417.
- [110] S. Höger, J. I. McNamara, S. Schriker, F. Wudl, *Chem. Mater.* 1994, 6, 171-173.
- [111] D.-H. Hwang, H.-K. Shim, J.-I. Lee, K.-S. Lee, *J. Chem. Soc. Chem. Commun.* 1994, 2461-2462.
- [112] C. Zhang, S. Höger, K. Pakbaz, F. Wudl, A. J. Heeger, *J. Electron. Mater.* 1994, 23, 453-458.
- [113] D.-H. Hwang, I.-N. Kang, M.-S. Jung, H.-K. Shim, T. Zyung, *Polym. Bull.* 1996, 36, 383-390.
- [114] S. T. Kim, D.-H. Hwang, X.-C. Li, J. Grüner, R. H. Friend, A. B. Holmes, H.-K. Shim, *Adv. Mater.* 1996, 8, 979-982.
- [115] M. Hamaguchi, K. Yoshino, *Jpn. J. Appl. Phys.* 1994, 33, L1478-L1481.
- [116] M. Hamaguchi, K. Yoshino, *Jpn. J. Appl. Phys.* 1995, 34, L712-L715.
- [117] G. Lüssem, F. Geffarth, A. Greiner, W. Heitz, M. Hopmeier, M. Oehrski, C. Unterlechner, J. H. Wendorff, *Liq. Cryst.* 1996, 21, 903-907.
- [118] Z. Yang, B. Hu, F. E. Karasz, *Macromolecules* 1995, 28, 6151-6154.
- [119] Z. Bao, Y. Chen, R. Cai, L. Yu, *Macromolecules* 1993, 26, 5281-5286.
- [120] P. L. Burn, A. B. Holmes, A. Kraft, D. D. C. Bradley, A. R. Brown, R. H. Friend, R. W. Gymer, *Nature* 1992, 356, 47-49.
- [121] P. L. Burn, A. Kraft, D. R. Baigent, D. D. C. Bradley, A. R. Brown, R. H. Friend, R. W. Gymer, A. B. Holmes, R. W. Jackson, *J. Am. Chem. Soc.* 1993, 115, 10117-10124.
- [122] E. Z. Faraghi, H. Chayot, G. Cohen, R. Neumann, Y. Aray, D. Davidov, *Adv. Mater.* 1995, 7, 742-745.
- [123] E. G. J. Staring, R. C. J. E. Demandt, D. Braun, G. L. J. Rikken, Y. A. R. R. Kessener, A. H. J. Vanhulzen, M. M. F. van Knippenberg, M. Bouwman, *Synth. Met.* 1995, 71, 2179-2180.
- [124] A. Kraft, P. L. Burn, A. B. Holmes, D. D. C. Bradley, A. R. Brown, R. H. Friend, R. W. Gymer, *Synth. Met.* 1993, 55, 936-941.
- [125] P. L. Burn, A. B. Holmes, A. Kraft, D. D. C. Bradley, A. R. Brown, R. H. Friend, *J. Chem. Soc. Chem. Commun.* 1992, 32-34.
- [126] A. R. Brown, P. L. Burn, D. D. C. Bradley, R. H. Friend, A. Kraft, A. B. Holmes, *Mol. Cryst. Liq. Cryst.* 1992, 216, 111-116.
- [127] C. Zhang, D. Braun, A. J. Heeger, *J. Appl. Phys.* 1993, 73, 5177-5180.
- [128] S. Son, A. Dodabalapur, A. J. Lovinger, M. E. Galvin, *Science* 1995, 269, 376-378.
- [129] H. Rost, A. Teuschel, S. Pfaffner, H. H. Hörhold, *Synth. Met.* 1997, 84, 269-270.
- [130] P. W. M. Blom, M. J. M. Dajong, J. J. M. Vleggaar, *Appl. Phys. Lett.* 1996, 68, 3308-3310.
- [131] A. Kraft, P. L. Burn, A. B. Holmes, D. D. C. Bradley, R. H. Friend, J. H. F. Martens, *Synth. Met.* 1993, 57, 4163-4167.
- [132] M. Yoshida, H. Kawahara, A. Fujii, Y. Ohmori, K. Yoshino, *Jpn. J. Appl. Phys.* 1995, 34, L1237-L1240.
- [133] C. Zhang, H. von Seggern, B. Kraebel, H.-W. Schmidt, A. J. Heeger, *Synth. Met.* 1995, 72, 185-188.
- [134] M. Berggren, M. Granström, O. Inganäs, M. Andersson, *Adv. Mater.* 1995, 7, 900-903.
- [135] T. Tsutsui, E.-I. Aminaka, Y. Fujita, Y. Hamada, S. Saito, *Synth. Met.* 1993, 57, 4157-4162.
- [136] X.-C. Li, A. Kraft, R. Cervini, G. C. W. Spencer, F. Cacialli, R. H. Friend, J. Grüner, A. B. Holmes, J. C. DeMello, S. C. Moratti, *Mat. Res. Soc. Symp. Proc.* 1996, 413, 13-22.
- [137] J. Bettenhausen, P. Strohrriegel, *Adv. Mater.* 1996, 8, 507-510.
- [138] J. Bettenhausen, P. Strohrriegel, *Macromol. Rapid Commun.* 1996, 17, 623-631.
- [139] A. Kraft, *Chem. Commun.* 1996, 77-79.
- [140] Q. Pei, Y. Yang, *Chem. Mater.* 1995, 7, 1568-1575.
- [141] F. Cacialli, X.-C. Li, R. H. Friend, S. C. Moratti, A. B. Holmes, *Synth. Met.* 1995, 75, 161-168.
- [142] M. Greczmiel, P. Pösch, H.-W. Schmidt, P. Strohrriegel, E. Buchwald, M. Meier, W. Ricas, M. Schwoerer, *Macromol. Symp.* 1996, 102, 371-380.
- [143] X.-C. Li, T.-M. Yong, J. Grüner, A. B. Holmes, S. C. Moratti, F. Cacialli, R. H. Friend, *Synth. Met.* 1997, 84, 437-438.
- [144] D. O'Brien, M. S. Weaver, D. G. Lidzey, D. D. C. Bradley, *Appl. Phys. Lett.* 1996, 69, 881-883.
- [145] M. Yoshida, A. Fujii, Y. Ohmori, K. Yoshino, *Jpn. J. Appl. Phys.* 1996, 35, L397-L400.
- [146] M. Hamaguchi, K. Yoshino, *Appl. Phys. Lett.* 1996, 69, 143-145.
- [147] M. Yoshida, A. Fujii, Y. Ohmori, K. Yoshino, *Appl. Phys. Lett.* 1996, 69, 734-736.
- [148] J.-L. Brédas, A. J. Heeger, *Chem. Phys. Lett.* 1994, 217, 507-512.
- [149] H.-H. Hörhold, M. Helbig, *Makromol. Chem. Macromol. Symp.* 1987, 12, 229-258.
- [150] N. C. Greenham, S. C. Moratti, D. D. C. Bradley, R. H. Friend, A. B. Holmes, *Nature* 1993, 365, 628-630.
- [151] N. C. Greenham, F. Cacialli, D. D. C. Bradley, R. H. Friend, S. C. Moratti, A. B. Holmes, *Mat. Res. Soc. Symp. Proc.* 1994, 328, 351-360.
- [152] S. C. Moratti, D. D. C. Bradley, R. H. Friend, N. C. Greenham, A. B. Holmes, *Mat. Res. Soc. Symp. Proc.* 1994, 328, 371-376.
- [153] S. C. Moratti, R. Cervini, A. B. Holmes, D. R. Baigent, R. H. Friend, N. C. Greenham, J. Grüner, P. J. Hamer, *Synth. Met.* 1995, 71, 2117-2120.
- [154] J. J. M. Hall, D. R. Baigent, F. Cacialli, N. C. Greenham, R. H. Friend, S. C. Moratti, A. B. Holmes, *Thin Solid Films* 1996, 276, 13-20.
- [155] D. R. Baigent, P. J. Hamer, R. H. Friend, S. C. Moratti, A. B. Holmes, *Synth. Met.* 1995, 71, 2175-2176.
- [156] S. C. Moratti, D. D. C. Bradley, R. Cervini, R. H. Friend, N. C. Greenham, A. B. Holmes, *Proc. SPIE Int. Soc. Opt. Eng.* 1994, 2144, 108-114.
- [157] R. M. Gurge, A. Sarkar, F. M. Lahli, B. Hu, F. E. Karasz, *Macromolecules* 1996, 29, 4287-4292.
- [158] Q. J. Sarnecki, R. H. Friend, A. B. Holmes, S. C. Moratti, *Synth. Met.* 1995, 69, 545-546.
- [159] A. Lux, A. B. Holmes, R. Cervini, J. E. Davies, S. C. Moratti, J. Grüner, F. Cacialli, R. H. Friend, *Synth. Met.* 1997, 84, 293-294.

REVIEWS

- [160] A. C. Grimsdale, X.-C. Li, F. Cacialli, J. Gruner, A. B. Holmes, S. C. Moratti, R. H. Friend, *Synth. Met.* 1996, 76, 165–167.
- [161] A. Lux, S. C. Moratti, X.-C. Li, A. C. Grimsdale, J. F. Davies, P. R. Rathby, J. Gruner, F. Cacialli, R. H. Friend, A. B. Holmes, *Polym. Prepr.* 1996, 37, 202–203.
- [162] M. Leclerc, F. M. Diaz, G. Wegner, *Makromol. Chem.* 1989, 190, 3105–3116.
- [163] H. Mao, S. Holdcroft, *Macromolecules* 1992, 25, 554–558.
- [164] H. Mao, B. Xu, S. Holdcroft, *Macromolecules* 1993, 26, 1163–1169.
- [165] Y. Ohmori, M. Uchida, K. Muro, K. Yoshino, *Jpn. J. Appl. Phys.* 1991, 30, L1938–L1940.
- [166] Y. Ohmori, M. Uchida, K. Muro, K. Yoshino, *Solid State Commun.* 1991, 80, 605–608.
- [167] D. Bamm, G. Gustafsson, D. McBranch, A. J. Heeger, *J. Appl. Phys.* 1992, 72, 564–568.
- [168] M. Uchida, Y. Ohmori, C. Morishima, K. Yoshino, *Synth. Met.* 1993, 57, 4168–4173.
- [169] N. C. Greenham, A. R. Brown, D. D. C. Bradley, R. H. Friend, *Synth. Met.* 1993, 57, 4134–4138.
- [170] A. Fujii, H. Kawahara, M. Yoshida, Y. Ohmori, K. Yoshino, *J. Phys. (D), Appl. Phys.* 1995, 28, 2135–2138.
- [171] A. Bolognesi, C. Botta, Z. Geng, C. Flores, L. Denti, *Synth. Met.* 1995, 71, 2191–2192.
- [172] M. Pomerantz, H. Yang, Y. Cheng, *Macromolecules* 1995, 28, 5706–5708.
- [173] R. E. Gill, G. G. Malliaras, J. Wildeman, G. Hadzioannou, *Adv. Mater.* 1994, 6, 132–135.
- [174] B. Xu, S. Holdcroft, *Macromolecules* 1993, 26, 4457–4460.
- [175] B. Xu, S. Holdcroft, *Proc. SPIE Int. Soc. Opt. Eng.* 1993, 1910, 65–68.
- [176] M. Berggren, G. Gustafsson, O. Inganäs, M. R. Andersson, O. Wennerström, T. Hjertberg, *Adv. Mater.* 1994, 6, 488–490.
- [177] M. Berggren, O. Inganäs, G. Gustafsson, J. Rasmussen, M. R. Andersson, T. Hjertberg, O. Wennerström, *Nature* 1994, 372, 444–446.
- [178] O. Inganäs, M. R. Andersson, G. Gustafsson, T. Hjertberg, O. Wennerström, P. Dyreklev, M. Granström, *Synth. Met.* 1995, 71, 2121–2124.
- [179] M. R. Andersson, M. Berggren, O. Inganäs, G. Gustafsson, J. C. Gustafsson-Carlberg, D. Sæse, T. Hjertberg, O. Wennerström, *Macromolecules* 1995, 28, 7525–7529.
- [180] Y. Miyazaki, T. Yamamoto, *Chem. Lett.* 1994, 41–44.
- [181] M. Berggren, G. Gustafsson, O. Inganäs, M. R. Andersson, T. Hjertberg, O. Wennerström, *J. Appl. Phys.* 1994, 76, 7530–7534.
- [182] M. C. Gallazzi, L. Castellani, G. Zerbi, P. Sozzani, *Synth. Met.* 1991, 41, 495–498.
- [183] M. R. Andersson, D. Sæse, M. Berggren, H. Järvinen, T. Hjertberg, O. Inganäs, O. Wennerström, J. E. Österholm, *Macromolecules* 1994, 27, 6503–6506.
- [184] R. D. McCullough, R. D. Lowe, *J. Chem. Soc. Chem. Commun.* 1992, 70–72.
- [185] R. D. McCullough, R. D. Lowe, M. Jayaraman, D. L. Anderson, *J. Org. Chem.* 1993, 58, 904–912.
- [186] R. D. McCullough, S. P. Williams, M. Jayaraman, J. Roddinger, L. Miller, S. Tristram-Nagle, *Mat. Res. Soc. Symp. Proc.* 1994, 328, 215–220.
- [187] R. D. McCullough, S. P. Williams, S. Tristram-Nagle, M. Jayaraman, P. C. Ewbank, L. Miller, *Synth. Met.* 1995, 69, 279–282.
- [188] T.-A. Chen, R. D. Rieke, *J. Am. Chem. Soc.* 1992, 114, 10087–10088.
- [189] T.-A. Chen, X. Wu, R. D. Rieke, *J. Am. Chem. Soc.* 1995, 117, 233–244.
- [190] C. A. Sandstedt, R. D. Rieke, C. I. Eckhardt, *Chem. Mater.* 1995, 7, 1057–1059.
- [191] F. Chen, F. G. Mehta, L. Takiff, R. D. McCullough, *J. Mater. Chem.* 1996, 6, 1763–1767.
- [192] K. A. Murray, S. C. Moratti, D. R. Baigent, N. C. Greenham, K. Pichler, A. B. Holmes, R. H. Friend, *Synth. Met.* 1995, 69, 395–396.
- [193] N. C. Greenham, I. D. W. Samuel, G. R. Hayes, R. T. Phillips, Y. A. R. R. Kessener, S. C. Moratti, A. B. Holmes, R. H. Friend, *Chem. Phys. Lett.* 1995, 241, 89–96.
- [194] R. D. McCullough, M. Jayaraman, *J. Chem. Soc. Chem. Commun.* 1995, 135–136.
- [195] K. A. Murray, A. B. Holmes, S. C. Moratti, R. H. Friend, *Synth. Met.* 1996, 76, 161–163.
- [196] P. Dyreklev, M. Berggren, O. Inganäs, M. R. Andersson, O. Wennerström, T. Hjertberg, *Adv. Mater.* 1995, 7, 43–45.
- [197] A. Bolognesi, G. Bojko, J. Palobaino, T. Östergård, H. Stubbs, *Adv. Mater.* 1997, 9, 121–124.
- [198] M. J. Marsella, T. M. Swager, *Polym. Prepr.* 1992, 33, 1196–1197.
- [199] J. Tian, C.-C. Wu, M. E. Thompson, J. C. Sturm, R. A. Register, M. J. Marsella, T. M. Swager, *Adv. Mater.* 1995, 7, 395–398.
- [200] J. Tian, C.-C. Wu, M. E. Thompson, J. C. Sturm, R. A. Register, *Chem. Mater.* 1995, 7, 2190–2198.
- [201] M. J. Marsella, D.-K. Fu, T. M. Swager, *Adv. Mater.* 1995, 7, 145–147.
- [202] H. L. Wang, M. J. Marsella, D.-K. Fu, T. M. Swager, A. G. MacDiarmid, A. J. Epstein, *Polym. Mater. Sci. Eng.* 1995, 73, 473–474.
- [203] L. S. Swanson, F. Lu, J. Shinar, Y. W. Ding, T. J. Barton, *Proc. SPIE Int. Soc. Opt. Eng.* 1993, 1910, 101–110.
- [204] C. Weder, M. S. Wrighton, *Macromolecules* 1996, 29, 5157–5165.
- [205] R. Giesa, *J. Macromol. Sci. Rev. Macromol. Chem. Phys.* 1996, 36, 631–670.
- [206] L. S. Swanson, J. Shinar, Y. W. Ding, T. J. Barton, *Synth. Met.* 1993, 55, 1–6.
- [207] C. Weder, M. J. Wagner, M. S. Wrighton, *Mat. Res. Soc. Symp. Proc.* 1996, 413, 77–84.
- [208] K. Tada, M. Onoda, M. Hirohata, T. Kawai, K. Yoshino, *Jpn. J. Appl. Phys.* 1996, 35, L251–L253.
- [209] K. Yoshino, K. Tada, M. Onoda, *Jpn. J. Appl. Phys.* 1994, 33, L1785–L1788.
- [210] M. Hay, P. L. Klavetter, *J. Am. Chem. Soc.* 1995, 117, 7112–7118.
- [211] G. G. Malliaras, J. K. Herrema, J. Wildeman, R. E. Gill, R. H. Wieringa, S. S. Lampoura, G. Hadzioannou, *Proc. SPIE Int. Soc. Opt. Eng.* 1993, 2025, 441–445.
- [212] G. G. Malliaras, J. K. Herrema, J. Wildeman, R. H. Wieringa, R. E. Gill, S. S. Lampoura, G. Hadzioannou, *Adv. Mater.* 1993, 5, 721–723.
- [213] J. K. Herrema, P. F. van Hutten, R. E. Gill, J. Wildeman, R. H. Wieringa, G. Hadzioannou, *Macromolecules* 1995, 28, 8102–8116.
- [214] F. Garten, A. Hilberer, F. Cacialli, E. Esselink, Y. van Dam, B. Schlattmann, R. H. Friend, T. M. Klapwijk, G. Hadzioannou, *Adv. Mater.* 1997, 9, 127–131.
- [215] D. Adam, R. Closs, T. Frey, D. Funhoff, D. Haurer, H. Ringsdorf, P. Schuhmacher, K. Siemensmeyer, *Phys. Rev. Lett.* 1993, 70, 457–460.
- [216] T. Christ, V. Stümpflen, J. H. Wendorff, *Macromol. Rapid Commun.* 1997, 18, 93–98.
- [217] T. Christ, B. Glisen, A. Greiner, A. Kettner, R. Sander, V. Stümpflen, V. Tsukruk, J. H. Wendorff, *Adv. Mater.* 1997, 9, 48–52.
- [218] Y. Ohmori, K. Uchida, K. Muro, K. Yoshino, *Jpn. J. Appl. Phys.* 1991, 30, L1941–L1943.
- [219] M. Fukuda, K. Sawada, K. Yoshino, *Jpn. J. Appl. Phys.* 1989, 28, L1433–L1435.
- [220] M. Fukuda, K. Sawada, K. Yoshino, *J. Polym. Sci. Polym. Chem.* 1993, 31, 2465–2471.
- [221] G. Grem, G. Leditzky, B. Ullrich, G. Leising, *Adv. Mater.* 1992, 4, 36–37.
- [222] G. Grem, G. Leditzky, B. Ullrich, G. Leising, *Synth. Met.* 1992, 51, 383–389.
- [223] K. Miyashita, M. Kaneko, *Synth. Met.* 1995, 68, 161–165.
- [224] D. L. Gin, V. P. Conticello, *Trends Polym. Sci.* 1996, 4, 217–223.
- [225] D. G. H. Ballard, A. Courtis, I. M. Shirley, S. C. Taylor, *J. Chem. Soc. Chem. Commun.* 1983, 954–955.
- [226] D. G. H. Ballard, A. Courtis, I. M. Shirley, S. C. Taylor, *Macromolecules* 1988, 21, 294–304.
- [227] D. R. McKean, J. K. Stille, *Macromolecules* 1987, 20, 1787–1792.
- [228] M. Hamaguchi, H. Sawada, I. Kyokame, K. Yoshino, *Chem. Lett.* 1996, 527–528.
- [229] A.-D. Schlüter, G. Wegner, *Acta Polym.* 1993, 44, 59–69.
- [230] T. Vahlenkamp, G. Wegner, *Macromol. Chem. Phys.* 1994, 195, 1933–1952.
- [231] T. F. McCarthy, H. Witteler, T. Pakula, G. Wegner, *Macromolecules* 1995, 28, 8350–8362.
- [232] M. Rommers, M. Schulze, G. Wegner, *Macromol. Rapid Commun.* 1996, 17, 239–252.
- [233] T. Yamamoto, *Progr. Polym. Sci.* 1992, 17, 1153–1205.
- [234] V. Percec, S. Okita, R. Weiss, *Macromolecules* 1992, 25, 1816–1823.
- [235] V. Percec, J.-Y. Bae, M. Zhao, D. H. Hill, *Macromolecules* 1995, 28, 6726–6734.

- [236] V. Percec, M. Zhao, J.-Y. Bae, D. H. Hill, *Macromolecules* 1996, 29, 3727–3735.
- [237] R. L. Klavetter, G. Gustafsson, A. J. Heeger, *Polym. Mater. Sci. Eng.* 1993, 69, 153–154.
- [238] W.-X. Jing, A. Kraft, S. C. Moratti, J. Gruner, F. Cacialli, P. J. Hamer, A. B. Holmes, R. H. Friend, *Synth. Met.* 1994, 67, 161–163.
- [239] M. Hamaguchi, K. Yoshino, *Jpn. J. Appl. Phys.* 1995, 34, L587–L589.
- [240] Y. Yang, Q. Pei, A. J. Heeger, *J. Appl. Phys.* 1996, 79, 934–939.
- [241] Y. Yang, Q. Pei, A. J. Heeger, *Synth. Met.* 1996, 78, 263–267.
- [242] V. Cimrová, W. Schmidt, R. Rulkens, M. Schulze, W. Meyer, D. Neher, *Adv. Mater.* 1996, 8, 585–588.
- [243] M. Remmers, D. Neher, J. Gruner, R. H. Friend, G. H. Gelinck, J. M. Warman, C. Quattrocchi, D. A. dos Santos, J.-L. Brédas, *Macromolecules* 1996, 29, 7432–7445.
- [244] U. Scherf, K. Müllen, *Makromol. Chem. Rapid Commun.* 1991, 12, 489–497.
- [245] U. Scherf, K. Müllen, *Macromolecules* 1992, 25, 3546–3548.
- [246] G. Leising, G. Grem, G. Leditzky, U. Scherf, *Proc. SPIE Int. Soc. Opt. Eng.* 1993, 1910, 70–77.
- [247] G. Grem, G. Leising, *Synth. Met.* 1993, 55–57, 4105–4110.
- [248] J. Hübner, K. Müllen, J. Salbeck, H. Schenk, U. Scherf, T. Stehlin, R. Stern, *Acta Polym.* 1994, 45, 244–247.
- [249] G. Grem, V. Martin, F. Meghdadi, C. Paar, J. Stampfl, J. Sturm, S. Tasch, G. Leising, *Synth. Met.* 1995, 77, 2193–2194.
- [250] U. Scherf, A. Bohnen, K. Müllen, *Makromol. Chem.* 1992, 193, 1127–1133.
- [251] G. Leising, G. Köpping-Grem, F. Meghdadi, A. Niko, S. Tasch, W. Fischer, L. Fu, M. W. Wagaman, R. H. Grubbs, L. Althouel, G. Froyer, U. Scherf, J. Huber, *Proc. SPIE Int. Soc. Opt. Eng.* 1995, 2528, 307–314.
- [252] S. Tasch, A. Niko, G. Leising, U. Scherf, *Appl. Phys. Lett.* 1996, 68, 1090–1092.
- [253] S. Tasch, A. Niko, G. Leising, U. Scherf, *Mat. Res. Soc. Symp. Proc.* 1996, 413, 71–76.
- [254] J. Gruner, H. P. Wittmann, P. J. Hamer, R. H. Friend, J. Huber, U. Scherf, K. Müllen, S. C. Moratti, A. B. Holmes, *Synth. Met.* 1994, 67, 181–185.
- [255] Y. Ohmori, M. Uchida, C. Morishima, A. Fujii, K. Yoshino, *Jpn. J. Appl. Phys.* 1993, 32, L1663–L1666.
- [256] Q. Pei, Y. Yang, *J. Am. Chem. Soc.* 1996, 118, 7416–7417.
- [257] M. Gröll, D. D. C. Bradley, M. Inbasekaran, E. P. Woo, *Adv. Mater.* 1997, 9, 798–802.
- [258] I. Sokolik, Z. Yang, F. E. Karasz, D. C. Morton, *J. Appl. Phys.* 1993, 74, 3584–3586.
- [259] Z. Yang, I. Sokolik, F. E. Karasz, *Macromolecules* 1993, 26, 1188–1190.
- [260] Z. Yang, F. E. Karasz, H. J. Geise, *Macromolecules* 1993, 26, 6570–6575.
- [261] D.-H. Hwang, I.-N. Kang, M.-S. Jang, H.-K. Shim, *Bull. Korean Chem. Soc.* 1995, 16, 135–138.
- [262] T. Zyung, D.-H. Hwang, I.-N. Kang, H.-K. Shim, W.-Y. Hwang, J.-I. Kim, *Chem. Mater.* 1995, 7, 1499–1503.
- [263] J.-K. Lee, R. R. Schrock, D. R. Baigent, R. H. Friend, *Macromolecules* 1995, 28, 1966–1971.
- [264] G. Yu, H. Nishino, A. J. Heeger, T.-A. Chen, R. D. Rieke, *Synth. Met.* 1995, 72, 249–252.
- [265] J. Birgersson, M. Pahlman, P. Bräms, W. R. Salaneck, *Synth. Met.* 1996, 80, 125–130.
- [266] N. Tanigaki, H. Masuda, K. Kacriyama, *Polymer* 1997, 38, 1221–1226.
- [267] T. Zyung, J.-I. Kim, I.-N. Kang, D.-H. Hwang, H.-K. Shim, *Mat. Res. Soc. Symp. Proc.* 1996, 413, 103–107.
- [268] I.-N. Kang, D.-H. Hwang, H.-K. Shim, T. Zyung, J.-I. Kim, *Macromolecules* 1996, 29, 165–169.
- [269] H. N. Cho, D. Y. Kim, Y. C. Kim, J. Y. Lee, C. Y. Kim, *Adv. Mater.* 1997, 9, 326–328; *Proc. SPIE Int. Soc. Opt. Eng.* 1997, 3418, 151–159.
- [270] M. Berggren, O. Inganäs, G. Gustafsson, M. R. Andersson, T. Hjertberg, O. Wennerström, *Synth. Met.* 1995, 71, 2185–2186.
- [271] M. Granström, O. Inganäs, *Appl. Phys. Lett.* 1996, 68, 147–149.
- [272] M. Uchida, Y. Ohmori, T. Noguchi, T. Ohnishi, K. Yoshino, *Jpn. J. Appl. Phys.* 1993, 32, L921–L924.
- [273] M. Yoshida, K. Yoshimoto, T. Akashi, M. Uchida, T. Kawai, Y. Ohmori, T. Noguchi, T. Ohnishi, K. Yoshino, *Synth. Met.* 1995, 71, 2111–2112.
- [274] M. Yoshida, A. Fujii, Y. Ohmori, K. Yoshino, *Jpn. J. Appl. Phys.* 1995, 34, L1546–L1549.
- [275] B. K. Cumpston, K. F. Jensen, *Trends Polym. Sci.* 1996, 4, 151–157.
- [276] B. H. Cumpston, I. D. Parker, K. F. Jensen, *J. Appl. Phys.* 1997, 81, 3716–3720.
- [277] M. Yan, L. J. Rothberg, F. Papadimitrakopoulos, M. E. Galvin, T. M. Miller, *Phys. Rev. Lett.* 1994, 73, 744–747.
- [278] T. Zyung, J.-I. Kim, *Appl. Phys. Lett.* 1995, 67, 3420–3422.
- [279] B. H. Cumpston, K. F. Jensen, *Synth. Met.* 1995, 73, 195–199.
- [280] R. D. Scurlock, B. Wang, F. R. Ogilby, J. R. Sheata, R. L. Clough, *J. Am. Chem. Soc.* 1995, 117, 10194–10202.
- [281] S. Karg, W. Riess, M. Meier, M. Schwoerer, *Mol. Cryst. Liq. Cryst.* 1993, 236, 79–86.
- [282] J. C. Scott, J. H. Kaufman, J. Salem, J. A. Goitia, P. J. Brock, R. DiPietro, *Mol. Cryst. Liq. Cryst.* 1996, 283, 57–62.
- [283] J. C. Scott, J. H. Kaufman, P. J. Brock, R. DiPietro, J. Salem, J. A. Goitia, *J. Appl. Phys.* 1996, 79, 2745–2751.
- [284] H. Aziz, G. Xu, *J. Phys. Chem. B* 1997, 101, 4009–4012.
- [285] Q. Pei, G. Yu, C. Zhang, Y. Yang, A. J. Heeger, *Science* 1995, 269, 1086–1088.
- [286] Y. Cao, G. Yu, A. J. Heeger, C. Y. Yang, *Appl. Phys. Lett.* 1996, 68, 3218–3220.
- [287] Q. Pei, Y. Yang, G. Yu, C. Zhang, A. J. Heeger, *J. Am. Chem. Soc.* 1996, 118, 3922–3929.
- [288] Q. Pei, Y. Yang, *Synth. Met.* 1996, 80, 131–136.
- [289] G. Yu, Q. Pei, A. J. Heeger, *Appl. Phys. Lett.* 1997, 70, 934–936.
- [290] Y. Yang, Q. Pei, *Appl. Phys. Lett.* 1996, 68, 2708–2710.
- [291] Y. Yang, Q. Pei, *J. Appl. Phys.* 1997, 81, 3294–3298.
- [292] Q. Pei, Y. Yang, G. Yu, Y. Cao, A. J. Heeger, *Synth. Met.* 1997, 85, 1229–1232.
- [293] Y. Yang, Q. Pei, *Appl. Phys. Lett.* 1997, 70, 1926–1928.
- [294] A. G. MacDiarmid, H.-L. Wang, J.-W. Park, D.-K. Fu, M. J. Marrella, T. M. Swager, Y. Wang, D. D. Gebler, A. J. Epstein, *Proc. SPIE Int. Soc. Opt. Eng.* 1995, 2528, 2–12.
- [295] Y. Z. Wang, D. D. Gebler, J. W. Blatchford, S. W. Jessen, L. B. Lin, T. L. Gustafsson, H.-L. Wang, Y. W. Park, T. M. Swager, A. G. MacDiarmid, A. J. Epstein, *Proc. SPIE Int. Soc. Opt. Eng.* 1995, 2528, 54–61.
- [296] Y. Z. Wang, D. D. Gebler, L. B. Lin, J. W. Blatchford, S. W. Jessen, H. L. Wang, A. J. Epstein, *Appl. Phys. Lett.* 1996, 68, 894–896.
- [297] H. L. Wang, A. G. MacDiarmid, Y. Z. Wang, D. D. Gebler, A. J. Epstein, *Synth. Met.* 1996, 78, 33–37.
- [298] A. J. Epstein, J. W. Blatchford, Y. Z. Wang, S. W. Jessen, D. D. Gebler, L. B. Lin, T. L. Gustafsson, H.-L. Wang, Y. W. Park, T. M. Swager, A. G. MacDiarmid, *Synth. Met.* 1996, 78, 253–261.
- [299] H. Wang, F. Huang, A. G. MacDiarmid, Y. Z. Wang, D. D. Gebler, A. J. Epstein, *Synth. Met.* 1996, 80, 97–104.
- [300] Y. Z. Wang, D. D. Gebler, D. K. Fu, T. M. Swager, A. J. Epstein, *Appl. Phys. Lett.* 1997, 70, 3215–3217.
- [301] H. F. Wittmann, J. Gruner, R. H. Friend, G. W. C. Spencer, S. C. Moratti, A. B. Holmes, *Adv. Mater.* 1995, 7, 541–544.
- [302] T. A. Fischer, D. G. Lidzey, M. A. Pate, M. S. Weaver, D. M. Whittaker, M. S. Skolnick, D. D. C. Bradley, *Appl. Phys. Lett.* 1995, 67, 1355–1357.
- [303] M. Berggren, O. Inganäs, T. Granlund, S. Guo, G. Gustafsson, M. R. Andersson, *Synth. Met.* 1996, 76, 121–123.
- [304] D. G. Lidzey, M. S. Weaver, T. A. Fischer, M. A. Pate, D. M. Whittaker, M. S. Skolnick, D. D. C. Bradley, *Synth. Met.* 1996, 76, 129–132.
- [305] V. Cimrová, D. Neher, *J. Appl. Phys.* 1996, 79, 3299–3307.
- [306] J. Gruner, F. Cacialli, R. H. Friend, *J. Appl. Phys.* 1996, 80, 207–215.
- [307] V. Cimrová, U. Scherf, D. Neher, *Appl. Phys. Lett.* 1996, 69, 608–610.
- [308] N. Tessler, G. J. Denton, R. H. Friend, *Nature* 1996, 382, 695–697.
- [309] F. Hide, M. A. Díaz-García, B. J. Schwartz, M. R. Andersson, Q. Pei, A. J. Heeger, *Science* 1996, 273, 1833–1836.
- [310] B. J. Schwartz, F. Hide, M. A. Díaz-García, A. J. Heeger, *Polym. Mater. Sci. Eng.* 1996, 75, 451–452.
- [311] S. V. Frolov, M. Ozaki, W. Gellermann, Z. V. Vardeny, K. Yoshino, *Jpn. J. Appl. Phys.* 1996, 35, L1371–L1373.

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- [312] H. J. Brouwer, V. V. Krasnikov, A. Hübner, G. Hadziioannou, *Adv. Mater.* 1996, 8, 935-937.
- [313] W. Halzer, A. Penzkofer, S.-H. Gong, A. Bleyer, D. D. C. Bradley, *Adv. Mater.* 1996, 8, 975-978.
- [314] S. V. Frolov, W. Gellermann, M. Ozaki, K. Yoshino, Z. V. Vardeny, *Phys. Rev. Lett.* 1997, 78, 729-732.
- [315] S. V. Frolov, W. Gellermann, Z. V. Vardeny, M. Ozaki, K. Yoshino, *Synth. Met.* 1997, 84, 471-472.
- [316] S. V. Frolov, M. Ozaki, W. Gellermann, M. Shkunov, Z. V. Vardeny, K. Yoshino, *Synth. Met.* 1997, 84, 473-474.
- [317] N. Tessler, G. J. Denton, R. H. Friend, *Synth. Met.* 1997, 84, 475-476.
- [318] D. G. Lidzey, D. D. C. Bradley, S. R. Alvarado, P. P. Seidler, *Nature* 1997, 386, 135.
- [319] D.-H. Hwang, S. T. Kim, H.-K. Shim, A. B. Holmes, S. C. Moratti, R. H. Friend, *Chem. Commun.* 1996, 2241-2242.
- [320] E. G. J. Staring, *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* 1996, 80, 111-117.
- [321] J. Birgersson, K. Kasriyama, P. Barta, P. Broms, M. Pahlman, T. Granlund, W. R. Salaneck, *Adv. Mater.* 1996, 8, 982-985.
- [322] M. R. Andersson, G. Yu, A. J. Heeger, *Synth. Met.* 1997, 85, 1275-1276.
- [323] M. Deußen, H. Bässler, *Chem. Unserer Zeit* 1997, 31, 76-86.
- [324] F. Hilde, M. A. Diaz-García, B. J. Schwartz, A. J. Heeger, *Acc. Chem. Res.* 1997, 30, 430-436.
- [325] M. Tüchlekkat, R. Fink, P. Pösch, J. Ring, H.-W. Schmidt, *Polym. Prepr.* 1997, 38, 323-324.
- [326] For a report by Meijer et al. in collaboration with Philips on circularly polarized electroluminescence from a polydialkoxypheylene vinylene), see E. Peeters, M. P. T. Christiaans, R. A. J. Janssen, H. F. M. Schoo, H. P. J. M. Dekkers, E. W. Meijer, *J. Am. Chem. Soc.* 1997, 119, 9909-9910.

Halogen Precursor Route to Poly[(2,3-diphenyl-*p*-phenylene)vinylene] (DP-PPV): Synthesis, Photoluminescence, Electroluminescence, and Photoconductivity

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ABSTRACT: Thin films of poly[(2,3-diphenyl-*p*-phenylene)vinylene] (DP-PPV) have been prepared via a chlorine precursor route (CPR). This involves the polymerization of 1,4-bis(chloromethyl)-2,3-diphenylbenzene with 1.0 equiv of potassium *tert*-butoxide to give the chlorine precursor polymer of DP-PPV. The chlorine precursor was thermally converted at different temperatures to give DP-PPV with different degrees of conversion. The conversion process was monitored by *in situ* photoluminescent (PL) spectroscopy. The onset of conversion was about 150 °C, and full conversion could be achieved at 170–250 °C. The degree of conversion was a function of the heating temperature rather than the duration of heating. The fully converted DP-PPV showed lower photoconductivity and higher PL intensity than PPV. Although partially converted DP-PPV showed bright PL, we have not been able to observe its EL. The electroluminescence (EL) of the single layer ITO/DP-PPV/Mg and the bilayer ITO/DP-PPV/Alq₃/Mg LED devices is also reported. A significant improvement in the quantum efficiency (up to 0.7% ph/el) and a reduction in the turn-on voltage of the device were found upon incorporation of the Alq₃ layer. These observations suggest that Alq₃ enhances the injection of electrons and also participates in the recombination process.

Introduction

The discovery of electroluminescence (EL) in poly(*p*-phenylenevinylene) (PPV)¹ has stimulated a great deal of interest in conjugated polymers and oligomers for solid state semiconductor device applications^{2–4} such as photovoltaic cells,^{5,6} xerographic photoconductors,⁷ field effect transistors,^{8–11} light-emitting diodes (LED),¹² and light-emitting electrochemical cells.^{13,14} PPV derived from the sulfonium precursor route (SPR) can be processed in many different ways to give PPV thin films with different luminescence characteristics.^{12,15} Enhancement of light-emitting efficiency and tuning of the color have been achieved.^{12,15} The approaches used for varying the luminescence properties of PPV include control of the conjugation length and side groups and modifications in processing for PPV.^{2,3,12,15}

The overall synthetic methodology for the preparation of PPV thin films can be divided into three main categories: (1) side chain derivatization, (2) precursor approach, and (3) *in situ* polymerization. We have focused on the first two methods and have prepared PPV and a wide range of PPV derivatives.^{2,16–20} Three precursor routes, namely the sulfonium precursor route (SPR),^{1,2} the halogen precursor route (HPR),^{2,17} and the xanthate precursor route (XPR),²¹ have been used for the fabrication of PPV LEDs. The three routes rely on the preparation of a soluble precursor polymer that is then cast into thin films and converted to the final

conjugated PPV films through heating. These three precursor routes are highly complementary to each other and have led to the synthesis of a wide range of PPV derivatives. Because of various synthetic difficulties, the SPR approach is limited and is useful mainly for the preparation of PPV.^{2,17–20} However, the water soluble polyionic sulfonium precursor polymer has enabled a unique opportunity for the fabrication of heterostructural LEDs via a self-assembly process.^{22,23} In general, XPR is useful for the preparation of PPV and those PPV derivatives with small side groups such as methyl and methoxy groups.²¹ The chlorine precursor route (CPR), one of many HPRs, is useful for the preparation of PPV with relatively large side groups such as phenyl, phenoxy, and hexyloxy.²⁴

We have focused our research on the fabrication of PPV-based LEDs via CPR.^{17–20} This effort has led to the recent communication of the fabrication of poly[(2,3-diphenyl-*p*-phenylene)vinylene] (DP-PPV) LED.¹⁸ We report here the synthesis and photophysical properties of DP-PPV synthesized via the CPR route. The conversion process of the soluble precursor polymer to DP-PPV thin films was studied by absorption and photoluminescence (PL) spectroscopies. The onset of conversion occurred at 150 °C, and a full conversion could be achieved at 170–250 °C. Fully converted DP-PPV has better electroluminescence and photoluminescence properties but lower photoconductivity relative to PPV. We have also demonstrated that by incorporating an electron transport layer to the DP-PPV LED device we can enhance the efficiency of EL.

Experimental Section

General Methods. All chemical reagents used were purchased from Aldrich. All organic solvents were used without any further purification. Distilled water was used in the reactions, and aqueous NaOH was freshly prepared for each reaction. ¹H NMR spectra were measured with a Bruker 360

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MHz spectrometer. Elemental analyses were performed by Galbraith Laboratories Inc. Melting points were measured using a Haake Buchler melting point apparatus and are uncorrected. GPC were measured on a Waters Modular system with a photodiode array and 410 refractive index. A 1% THF solution of the precursor polymer with THF as the eluent and polystyrene standard was used. Infrared measurements were made on a Perkin-Elmer 1750 FTIR.

Thin polymer films for optical absorption and photoluminescence were prepared by spin casting of a 1 wt % toluene solution of the precursor polymer onto a glass substrate, yielding a polymer film approximately 400 Å thick. Each sample was heated at a preselected temperature under a flow of dry nitrogen for 2 h. The samples were stored under low vacuum. Photophysical measurements were made at room temperature, in air or under an argon atmosphere. UV-visible spectra were obtained on a Perkin-Elmer Lambda 9 spectrophotometer. Steady state PL measurements were done on a Spex Fluorolog-2 fluorometer equipped with a DM3000F spectroscopy computer, where the samples were positioned such that the emission was detected at 22.5° from the incident beam. PL was also monitored from the conversion chamber with a Photo-Research SpectraScan 650 photocalorimeter. The emission spectra were obtained at 380 nm with an excitation power of 1 mW/cm².

Time-resolved DP-PPV film decay measurements were performed using time-correlated single photon counting. The excitation system consisted of a mode-locked frequency-doubled Nd:YAG laser (Quantum Model 418) synchronously pumping a cavity-dumped dye laser (Coherent model 703D) circulating rhodamine 6G. The dye laser pulses were typically 10 ps in duration at a repetition rate of 38 MHz with an excitation wavelength of 380 nm. The time-resolved emission spectra were taken under different storage and measurement conditions to study the effects of air exposure on the samples. The spectra are normalized to the same height for visual clarity. Samples were stored under low vacuum or in air after conversion, and sample measurements were also performed in air or under continuous nitrogen flow.

A free-standing DP-PPV film was prepared for photoconductivity measurement as follows: About 2.0 mL of a 2.0 wt % chlorine precursor polymer in toluene was transferred onto a leveled 2.0 in. × 2.0 in. glass substrate and then covered with a Petri dish to allow slow solvent evaporation. The dried film was then converted at 200–250 °C for 2 h under an argon atmosphere. Upon cooling, the film was lifted from the substrate with dry ice. Two aluminum contacts were deposited onto opposite sides of the film by vacuum deposition. The samples were mounted in an electrically shielded box and in some instances in a vacuum chamber. Illumination was in the applied field direction. The light source used was a xenon lamp dispersed by a holographic grating monochromator broadcasting into an optical fiber bundle. A computer-controlled stepper motor was employed for wavelength dependence studies. A series of neutral density filters were used to regulate the light intensity. Current vs voltage characteristics were measured using an electrometer and a digital power supply under computer control. The spectra shown are presented without correction due to losses caused by the electrodes.

EL emission spectra were performed on an Oriol InstaSpec IV CCD system equipped with a imaging monochromator model Oriol MS127i. An optical fiber was used to couple the EL light to the monochromator. The output of the CCD array was stored and processed by a personal computer. The emission PL and EL spectra shown in this paper have not been corrected for possible distortions due to monochromators. The luminance-current-voltage measurements were performed by using an HP 4155A Semiconductor Parameter Analyzer. A silicon photodiode (area 1 cm²) was placed in front of the EL device and used for both the efficiency and luminance measurements. Two different calibrations were used: one estimated the external quantum efficiency by using an integrating sphere, and the other estimated the luminance by using a photometer aimed directly at the emitting area. The electrical

and optical measurements presented here were performed under dry nitrogen and ambient conditions, respectively.

2,5-Dicarbethoxy-3,4-diphenylcyclopentadienone (1). To a cooled solution of benzil (83.0 g, 300 mmol) and diethyl acetonedicarboxylate (72.6 g, 0.96 mol) in methanol (200 mL) was slowly added a solution of NaOH (12.0 g, 300 mmol) in methanol (12 g in 60 mL) with stirring. The mixture was warmed to room temperature and stirred overnight. The resultant yellow precipitate was filtered off and dried. H₂SO₄ was then added dropwise with stirring to a slurry of the yellow precipitate in acetic anhydride (350 mL) until all of the yellow precipitate had dissolved. An additional five drops of H₂SO₄ was then added to the solution. Finally, while the temperature of the solution was maintained below 90 °C, water was added dropwise to decompose excess acetic anhydride. The resultant orange precipitate was filtered off, air dried, and recrystallized from ligroine (100.5 g, 92%): mp 119–121 °C (lit. 120–121 °C).²⁵

Diethyl 2,3-Diphenyl-1,4-benzenedicarboxylate (2). A solution of 1 (20 g, 55 mmol) and norbornadiene (24.48 g, 265 mmol) in toluene (75 mL) was refluxed for 5 h. The volume of solvent was reduced to 15 mL and methanol was added slowly to give a white precipitate. The white solid was filtered and recrystallized from methanol (17.3 g, 84%): mp 106–107 °C (lit. 110–112 °C).²⁵

1,4-Bis(hydroxymethyl)-2,3-diphenylbenzene (3). A solution of 2 (17.8 g, 46 mmol) in anhydrous THF (175 mL) was added dropwise with stirring to a suspension of LiAlH₄ (7.89 g, 208 mmol) in anhydrous THF (350 mL) over a 30 min. period at 0 °C. The solution was stirred at room temperature for 1 h and then refluxed for an additional 5 h. The solution was then cooled in an ice bath, and with continuous stirring, water (8 mL) was added dropwise over 15 min. This was followed by 16% NaOH (24 mL) for another 15 min, and finally water (24 mL) was added over a 15 min period. The resulting mixture was stirred for 12 h and filtered, and then the product was recrystallized from aqueous methanol to give a white solid (11.61 g, 87%): mp 190–192 °C; IR (KBr) 3076–3022 (aromatic C–H), 2910–2868 (aliphatic C–H), 3346–3349 cm⁻¹ (OH); ¹H NMR (DMSO-*d*₆) δ 4.3 (d, 4 H), 5.0 (t, 2 H), 7.05 (m, 10 H), 7.67 (s, 2 H); ¹³C NMR (DMSO-*d*₆) δ 61.15, 125.62, 126.13, 127.30, 129.61, 138.24, 138.66, 138.86; MS *m/e* (relative intensity (%)) 290 (100, M⁺). Anal. Calcd for C₂₀H₁₈O₂: C, 82.73; H, 6.25. Found: C, 82.72; H, 6.03.

1,4-Bis(chloromethyl)-2,3-diphenylbenzene (4). A mixture of 3 (5 g, 17.2 mmol) and thionyl chloride (31 g, 260 mmol) was stirred overnight, and then the excess thionyl chloride was removed. The pale yellow product was then recrystallized from methanol (4.43 g, 78.9%): mp 97–99 °C; IR (KBr) 3057–3022 (aromatic C–H), 2966 cm⁻¹ (aliphatic C–H); ¹H NMR (CDCl₃) δ 4.29 (s, 4 H), 7.0 (s, 10 H), 7.7 (s, 2 H); ¹³C NMR (ODCl₃) δ 44.45, 126.61, 127.47, 129.37, 129.95, 135.95, 137.67, 141.63. MS *m/e* (relative intensity (%)) 327 (4.59, M⁺), 255 (100). Anal. Calcd for C₂₀H₁₆Cl₂: C, 73.41; H, 4.93. Found: C, 73.57; H, 4.87.

Poly[(2,3-diphenyl-*p*-phenylene)(2-chloroethylene)] (5). A 3 mL aliquot of *t*-BuOK (1.0 M in THF) was added to a solution of 4 (1.0 g, 3.0 mmol) in THF (40 mL). The resulting solution was then stirred for 1 h at room temperature before being precipitated from methanol (200 mL). The precipitate was filtered off and air dried to give the chlorine precursor polymer (light yellow in color). The number and weight average molecular weights of the precursor polymer were 211 609 and 1 119 499 with an *M_w/M_n* ratio of 5.3, as determined by gel permeation chromatography. Anal. Calcd for C₂₀H₁₅Cl: C, 82.61; H, 5.20; Cl, 12.19. Found: 82.42; C, 5.29; H, Cl, 11.68 (Cl indicating a 6% conversion based on the chlorine content).

Poly[(2,3-diphenyl-*p*-phenylene)(2-chloroethylene)-phenylene(2-chloroethylene)]. *t*-BuOK (1.0 M) in THF (3 mL) was added to a solution containing 4 (0.5 g, 1.5 mmol) and 1,4-bis(chloromethyl)benzene (0.5 g, 1.5 mmol) in THF (45 mL). The resulting solution was then stirred for 1 h at room temperature before being precipitated from methanol (300 mL). The precipitate was filtered off and air dried to give the chlorine precursor copolymer of DP-PPV and PPV. Elemental

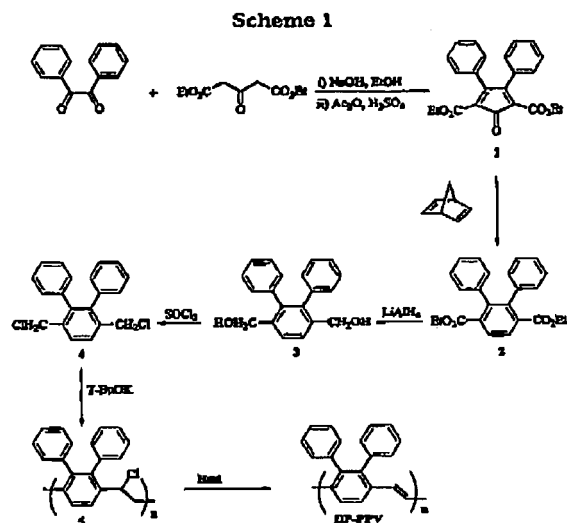


Table 1. Degree of Conversion of DP-PPV under Different Thermal Conditions

conditions	% C	% H	% Cl	total	deg of conv
as obtained (5)	82.42	5.29	11.68	99.39	5.0
280 °C/2 h	92.12	5.55	1.84	99.51	88.0
280 °C/3 h	93.58	5.56	0.50	99.73	97.0
DP-PPV (theory)	94.50	5.50	0	100.0	100.0

analysis showed 78.34% C, 5.27% H, and 14.40% Cl, corresponding to a precursor copolymer ratio of 4:1 DP-PPV to PPV (theory for a 4:1 ratio is 79.70% C, 5.44% H, and 14.86% Cl).

Results and Discussion

Synthesis. The monomer, 1,4-bis(chloromethyl)-2,3-diphenylbenzene was prepared in a four-step reaction according to Scheme 1. The condensation of benzil and diethyl acetonedicarboxylate in the presence of sodium hydroxide, followed by dehydration in acetic anhydride/sulfuric acid, gives 1.²⁵ This undergoes the Diels-Alder reaction with norbornadiene to give 2. The reduction of 2 with LiAlH_4 gives 3, which is then converted to 4 with thionyl chloride. The monomer 4 is then polymerized by treatment with 1.1 equiv of potassium tert-butoxide ($t\text{-BuOK}$) to give the chlorine precursor polymer 5. The precursor polymer 5 showed M_n and M_w of 1119 499 and 211 603, respectively. Elemental analysis showed 82.42% carbon, 5.29% hydrogen, and 11.68% chlorine, indicating 5% conversion had occurred, based on the chlorine content. The polymerization of 4 with a 1.1 equiv of $t\text{-BuOK}$ gives mostly soluble precursor polymer. Insoluble precursor polymers were obtained when 1.7 equiv of base was used. 5 is solvent cast onto a glass substrate and converted to DP-PPV, 6, as a free-standing film (see Experimental Section) by thermal conversion at different conversion temperatures. The elemental analysis of DP-PPV converted at different temperatures showed different degrees of conversion based on the chlorine content, as shown in Table 1.

The Infrared spectra of 5 (top) and DP-PPV (bottom) converted at 230 °C are shown in Figure 1. They are very similar except for an additional peak at 968 cm^{-1} for DP-PPV, which is attributed to the out of plane deformation of trans C-H. A small amount of conversion of 5, which was confirmed by elemental analysis, is evident in the IR with a vinylic C-H stretching

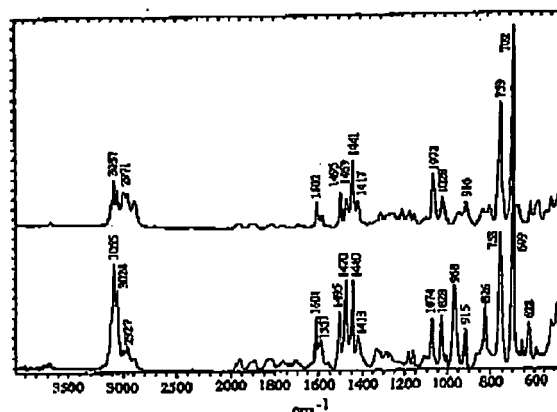


Figure 1. Infrared spectra of the polymer precursor 5 (top) and DP-PPV which was converted at 230 °C (bottom).

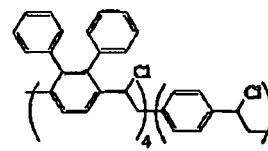
Table 2. Experimental Conditions Used for the Synthesis of Poly(DP-PPV-co-PPV)

amt of 1,4-bis(chloromethyl)- 2,3-diphenylbenzene (mmol)	amt of 1,4-bis(chloro- methyl)benzene (mmol)	amt of $t\text{-BuOK}$ (mmol)	THF (mL)	yield (%)	result
2.14	0.97	18	46	37	insoluble
1.5	1.5	18	46	53	insoluble
1.5	1.5	3.2	45	28	soluble

peak at 3057 cm^{-1} . This peak becomes very pronounced for DP-PPV at 3065 cm^{-1} .

We have also attempted to prepare poly(DP-PPV-co-PPV). Highly insoluble poly(DP-PPV-co-PPV) was obtained from copolymerization of 4 and 1,4-bis(chloromethyl)benzene with a large excess of base (see Table 2).

We obtained a soluble precursor of poly(DP-PPV-co-PPV) with M_n and M_w of 818 780 and 31 148, respectively and a M_w/M_n ratio of 26 by using a 1:1 equivalent of base. It is interesting to note that a relatively narrow molecular weight distribution of 5.9 was obtained for DP-PPV while a broad molecular weight distribution of 26 was obtained for poly(DP-PPV-co-PPV) under similar polymerization conditions. Broad molecular weight distributions are not unknown, and the high M_w/M_n ratio is probably attributed to a distribution of polymeric chains of the copolymer. This may be due to the reaction conditions used for the polymerization procedure or possibly due to the different solubilities of monomers of PPV and DP-PPV. In addition, we did not optimize the molecular weight distributions for this copolymer. The observed elemental analysis data of 78.34% C, 5.27% H, and 14.40% Cl for the copolymer precursor corresponds well with the calculated values of 79.70% C, 5.44% H, and 14.86% Cl for the following formula:



Optical Absorption and Photoluminescence of DP-PPV Converted at Different Temperatures. The conversion process of 5 in the form of thin films (400 Å) under nitrogen or high vacuum was investigated

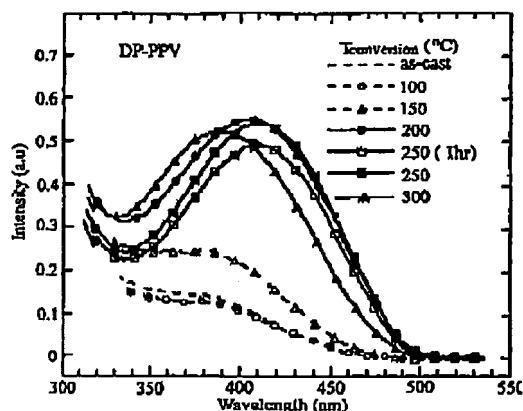


Figure 2. Absorption spectra of DP-PPV thermally converted at different conversion temperatures.

by absorption and emission spectroscopy. The thermal conversion of (5) was performed at different temperatures. Figure 2 shows the absorption spectra of (5) for a set of samples converted at different temperatures between 100 and 300 °C for 2 h. The spectrum of the sample converted at 100 °C is almost identical to that of the precursor polymer. This indicates that thermal conversion does not easily occur at <100 °C, and that 5 is relatively robust. In fact, (5) can be stored under ambient conditions for more than 1 year without any detectable deterioration.

A weak absorption band at 390 nm emerges for the sample converted at 150 °C, which is indicative of thermal conversion. A relatively strong π - π^* absorption band at 405 nm can be seen for the sample converted at 200 °C. The absorption band shows a red shift to 410 nm for the sample converted at 250 °C relative to the sample at 200 °C. The absorption band for the 300 °C sample shows a blue shift to about 385 nm and a reduction in intensity. These observations indicate that by increasing the temperature of thermal conversion from 150 to 250 °C, higher conjugation lengths and higher degrees of conversion can be achieved. At 300 °C, a reduction in intensity with a concurrent blue shift in the UV spectrum indicates thermal decomposition of the conjugated polymer. The λ_{max} at 405 nm and the band edge at 590 nm for DP-PPV are both blue shifted by approximately 30–40 nm with respect to PPV. This may be due to ineffective conjugation along the DP-PPV polymer backbone caused by steric hindrance of the bulky diphenyl groups. The bulky phenyl groups also result in low crystallinity for DP-PPV, which is reflected by the smooth π - π^* absorption band without vibronic structure similar to the case of PPV with phenyl substituents.^{26,27} The featureless spectrum is caused by disorder induced by the bulky phenyl substituents.

The steady state photoluminescent emission spectra for the same set of samples described above are shown in Figure 3. The PL spectra of the samples converted at 100 and 150 °C are essentially identical to that of the precursor polymer 5, indicating the partially converted nature of these samples and the presence of identical emitting species. A red spectral shift is observed for the samples converted at 200 and 250 °C, which is indicative of their transformation to DP-PPV. The significant PL intensity drop for the 300 °C sample is attributed to thermal decomposition that forms defects which serve as the quenching sites. However,

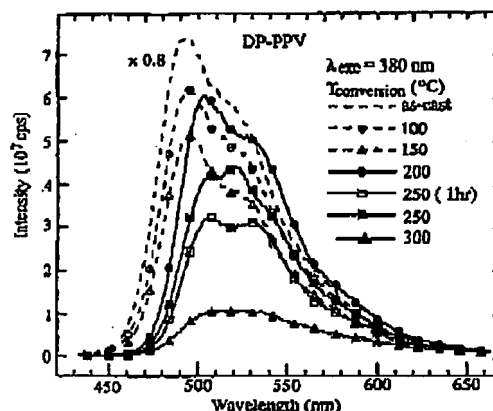


Figure 3. Emission spectra of DP-PPV thermally converted at different conversion temperatures.

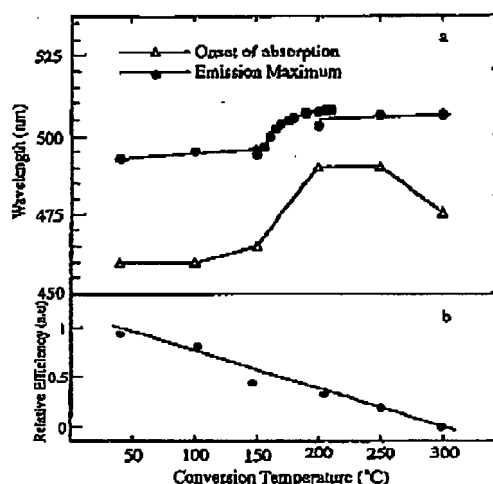


Figure 4. (a) Onset of the absorption and the main emission peak positions plotted as a function of the wavelength. A red shift occurs after the conversion temperature reaches 200 °C. (b) Plot of relative quantum efficiency of DP-PPV vs conversion temperature, which is decreasing with increasing conversion temperatures.

there is little spectral shift for the 300 °C sample, indicating that the emitting species remain the same as those samples converted at 200 and 250 °C.

In order to have a better understanding of the conversion process, we performed *in situ* PL measurements on a sample while it was being heated in the temperature range 150–200 °C (Figure 4a). Shown in Figure 4a is the progression of the spectral shifts with respect to the conversion temperature. Both the band edge and the emission peak plots clearly show that 150 °C is the onset of thermal conversion and that 200–250 °C are the optimal conversion temperatures for achieving full conversion. A red shift in the emission spectra occurs continuously between 150 and 170 °C. Such a change was also observed in PPV where the red shift did not occur below 210 °C.²⁷ At 200 °C, both absorption and emission spectra of DP-PPV, have shifted to the red and stayed at these positions even at higher temperatures. The absorption spectrum's rising edge is at 490 nm, which is 30–40 nm blue-shifted relative to PPV. Steric hindrance by the phenyl sub-

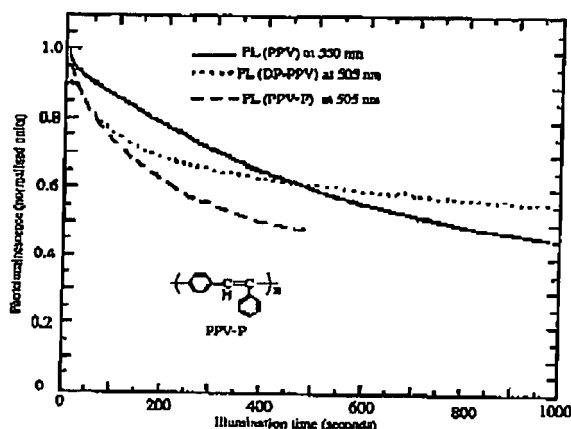


Figure 5. Comparison of the photoluminescence degradation with light exposure of DP-PPV, PPV, and PPV-P.

stituents results in less effective conjugation as compared to PPV.²⁸ The red shift of the steady state spectra when the temperature reaches 160–170 °C infers that the conversion has a well-defined thermodynamic barrier. As the temperature increases from 200 °C, the relative quantum efficiency decreases with the conversion temperature but the spectral position remains unchanged (Figure 4b), which appears to indicate that the polymer becomes more crystalline as the temperature increases. We have reported previously that DP-PPV showed crystallinity according to X-ray diffraction studies.³⁰ However, electron diffraction studies of DP-PPV as a function of conversion temperature are needed to show if the decrease in luminescence that accompanies the increase in temperature is due to increased crystallinity. Photoluminescence efficiency decreases as a result of self-quenching due to a higher concentration of light-emitting centers. For the sample converted at 300 °C, the absorption spectrum exhibits a blue shift. When the conversion temperature reaches that high, decomposition and defect formation can take place. Carbonyl formation may lead to the breakdown of the polymer, which results in shorter conjugation lengths that have been reported for PPV.^{23,29} This change in the chemistry of the polymer becomes predominant and is reflected by the slight blue shift of the absorption spectrum. Prolonged heating to 5 h under nitrogen at 250 °C did not produce any changes in the absorption or emission spectra of the sample. This indicates that the conversion of DP-PPV depends mainly on the temperature at which the sample is heated.

We examined the degradation of the PL as a function of the illumination time of DP-PPV, PPV, and PPV-P thin films (Figure 5). Time course PL studies indicate that initially, DP-PPV has an exponential like decay profile, as a function of the duration of light exposure under ambient conditions (light intensity is 1 mW/cm²), unlike PPV, which appears almost linear in its initial decay profile. This difference in the initial decay profile for DP-PPV and PPV could imply different decay mechanisms. After 400 s, the decay profile of DP-PPV becomes similar to those reported for PPV and PPV-P (Figure 5). The PL decay can be prevented in DP-PPV by illuminating under a N₂ atmosphere, indicating photooxidation may be occurring, which is in agreement with that observed by others for PPV.^{30–32}

Time-Resolved Emission Decay of DP-PPV Converted at Different Temperatures. We present in

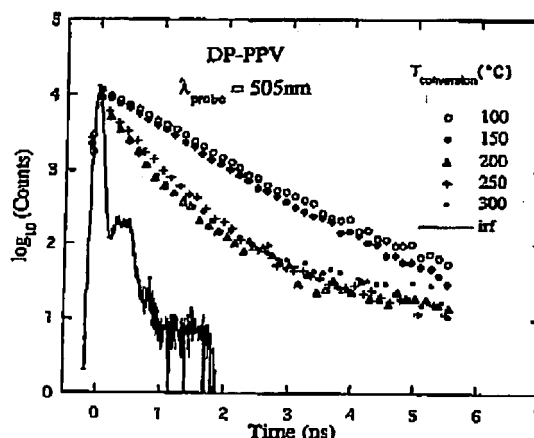


Figure 6. PL decay dynamics of DP-PPV probed at different temperatures. The single exponential decay when the conversion temperature is below 200 °C becomes more complex as the conversion temperature is above 200 °C.

Figure 6 the time-resolved PL spectra probed at the emission peak maximum, 495 nm, for conversion temperatures below 150 °C and 505 nm for the conversion temperatures above 200 °C. Figure 6 shows that the PL decay lifetime (the time for the emission intensity to fall to 1/e of the initial PL) decreases from 1.17 to 1.02 ns as the conversion temperature increases from 100 to 150 °C. Faster decay in a more conjugated PPV has also been previously reported.³³ An increase in traps such as by carbonyl groups via photooxidation to account for the time-resolved emission spectra was discounted since we did not observe any peaks due to carbonyl groups in the infrared spectra of 5 and DP-PPV converted at 230 °C (Figure 1).

In the partially converted polymer, the single exponential decay points to one type of emitting chromophore and to a very localized exciton. Segments of oligo conjugated chains are separated from each other by the leaving group and other defects and can emit independently with little self-quenching. At 200–300 °C, the decay curves become even faster and the behavior becomes more complex. The decay lifetime for DP-PPV converted at 200–300 °C is about 0.32–0.42 ns. We know that the fully converted DP-PPV can be obtained at this temperature range. Nonradiative decay paths involving self-quenching by the interchain excitons³⁴ and/or exciplexes^{35,36} is highly possible in the fully converted state due to the high concentration of the excited species. A shorter lifetime decay infers a larger mobility of the excitons.³⁷ The more rapid motion of the excitons accounts for the decrease in intensity of the steady-state emission as the conversion temperature increases. More excitons nonradiatively decay because of a larger probability of interaction with quenching sites. The nonsingle exponential behavior of the decay points to the existence of two processes for the light emission. The decays signal has a fast and a slow component. The fast component of the PL may be due to direct emission from the intrachain exciton, while the slow PL may be from interchain excitons re-formed to intrachain excitons.³⁴

Photoconductivity for Free Standing Films of DP-PPV. The photoconductivity (PC) response and the subsequent relaxation for DP-PPV thin films (10 nm) are presented in Figure 7. An electric field of about 105

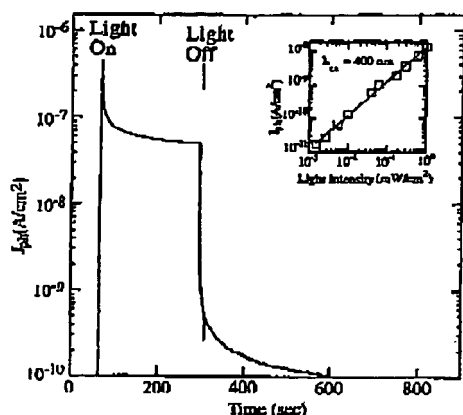


Figure 7. Buildup and decay of the steady state PC as a function of time. The applied field is 10^5 V/cm, and the monochromatic light is $\lambda_{\text{exc}} = 400$ nm. DP-PPV exhibits a strong PC response. The sublinear behavior of the photocurrent with the incident light is shown in the inset.

V/cm was applied across the device, and the sample was subjected to monochromatic light (400 nm) with light intensity of 0.3 mW/cm^2 for approximately 210 s. Under these conditions, the conductivity of the sample increased instantaneously by more than 8 orders of magnitude upon light exposure but decayed sharply to reach a steady-state after more than 50 s. This relaxation is an extrinsic effect and it was found to be more pronounced as the sample was exposed to air and to continuous illumination. The photocurrent relaxation upon illumination may be attributed to the relaxation of the electric field within the device caused probably by the space charge of trapped photocarriers or by other time dependent contact related effects commonly observed in these materials. Furthermore, when the light is off, the initial drop of the photocurrent is followed by a persistent current tail supporting the speculation of delayed emission of trapped carriers. The inset in Figure 7 shows the linear dependence of the photocurrent with the light intensity at $\lambda = 400$ nm and electric field of about 10^5 V/cm. The linear relation between the photocurrent and the light intensity suggests that the photocarrier generation rate is proportional to the number of photons absorbed and suggests that the density of photocarriers is low enough where bimolecular dynamics are not present. Figure 8 displays the spectral response of photoconductivity of DP-PPV together with its optical absorption spectrum. Each data point in the PC spectrum was measured 50 s after the light was turned on to allow the signal to reach equilibrium. Light intensity in the PC measurements were reduced by the use of neutral filters with an optical density totaling 2.0. The steady-state response of PC shows a threshold at about 490 nm, almost coincident with the onset of the $\pi-\pi^*$ interband transition in the tail of the absorption spectrum, and a peak at a position coinciding with the absorption maximum at 410 nm. The electric field dependence of the photocurrent for the free standing DP-PPV is shown in Figure 9. For this experiment the sample was kept in the cryostat and measurement was made under vacuum (10^{-2} Torr) and also in a dry oxygen atmosphere. The photocurrent was obtained by illumination at $\lambda = 400$ nm and at the intensity of 0.3 mW/cm^2 . There was no significant difference in the photocurrent when testing conditions

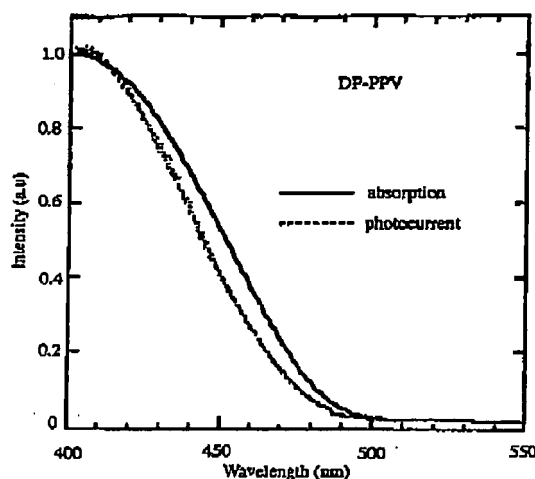


Figure 8. Optical absorption (full line) and the spectral response of the photocurrent (broken line) at an electric field of 10^5 V/cm.

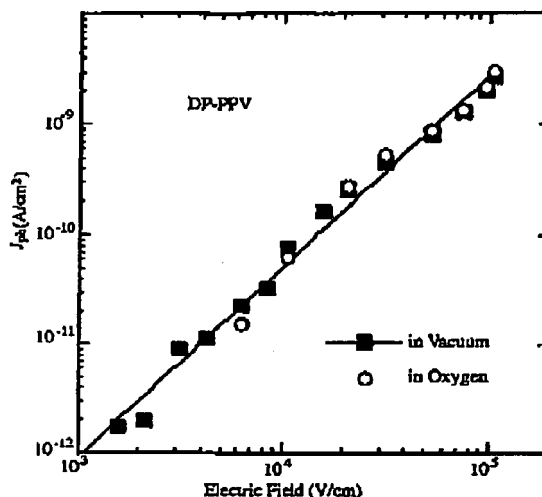


Figure 9. Electric field dependence of the photocurrent density at $\lambda_{\text{exc}} = 400$ nm and light intensity of about 0.3 mW/cm^2 .

were changed from vacuum to oxygen. This indicates that the photogeneration is not influenced by molecular oxygen and if there is any oxidation it affects only the very top surface of DP-PPV. In general the photoconductivity of DP-PPV was found to be much lower than that of PPV. In an earlier publication⁶ we found that ITO/PPV/Al devices, under similar conditions of illumination and electric field, can produce photocurrent densities in excess of 10^{-6} A/cm^2 . Even higher photocurrent densities were detected in coplanar structures of PPV having gold or aluminum electrodes.⁸⁸ The low photocurrents and the absence of bimolecular recombination detected in DP-PPV devices may be related to higher density of traps present in this polymer or to a lower photocarrier generation efficiency with respect to PPV. More work needs to be done to clarify these issues further.

Electroluminescence of Single Layer and Bi-layer DP-PPV LED Devices. For fabrication of the

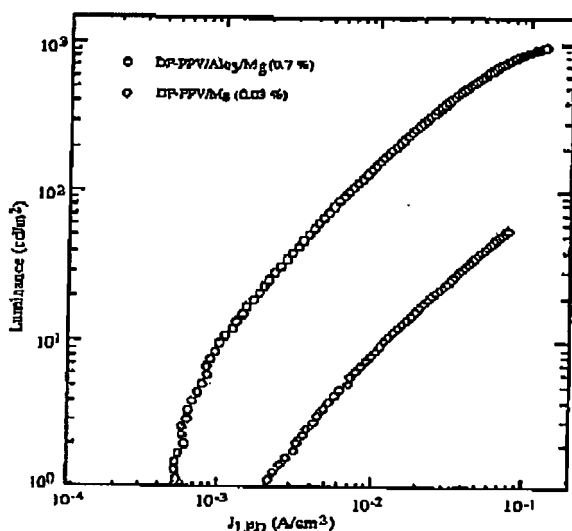


Figure 10. Luminance versus injection current density for single layer (ITO/DP-PPV/Mg) and bilayer (ITO/DP-PPV/Alq₃/Mg) devices. At 10 mA/cm² the corresponding external quantum efficiencies are 0.03% and 0.7% ph/el, respectively.

DP-PPV LED devices, 5 was spin cast onto a indium-tin-oxide (ITO) coated glass substrate and converted to DP-PPV at 270 °C for 2 h under an inert atmosphere. Magnesium was then deposited on top of DP-PPV by vacuum evaporation to make the single layer ITO/DP-PPV/Mg LED device. The bilayer device consisted of an additional layer of tris(8-hydroxyquinoline)aluminum (Alq₃) located between DP-PPV and the Mg layer (ITO/DP-PPV/Alq₃/Mg). The EL spectra of the single layer and bilayer DP-PPV devices are similar, with the maximum at 500 nm. The EL spectra are virtually identical to the PL spectra converted at the same temperature except for a slight red shift. The similarities of the PL and EL spectra are in agreement with the spectra reported for other LEDs made from PPV and its derivatives, such as MEH-PPV and BOHA-PPV, which suggests that the same excitations are involved.^{1,39,40}

Emissions of uniform green light were detected from the ITO/DP-PPV/Mg device with a turn-on voltage of 3 V. The turn-on voltage is one of the lowest observed for single layer conjugated polymer devices and is comparable to those reported for polymer/Ca devices.^{40,41} The external EL quantum efficiency of ITO/DP-PPV/Mg is 0.04% ph/el (photons emitted per electrons injected). This is in contrast to the bilayer ITO/DP-PPV/Alq₃/Mg LED device, which shows a 20-fold increased quantum efficiency (0.7% ph/el).⁴² This effect is illustrated in Figure 10, in which the luminance is plotted as a function of the injection current for the bilayer ITO/DP-PPV/Alq₃/Mg and the single layer ITO/DP-PPV/Mg devices. The improved efficiency for the bilayer device must be related to the improved injection of electrons from Mg to Alq₃ as well as the efficient electron transport within Alq₃. This layer also acts as a barrier to the holes and prevents them from reaching the Mg cathode. We have also plotted in Figure 11 the luminance as a function of the average applied electric field, which is defined as V/d , where d is the thickness of the DP-PPV layer and V is the applied voltage. The Alq₃ in the bilayer reduces the operating voltage considerably

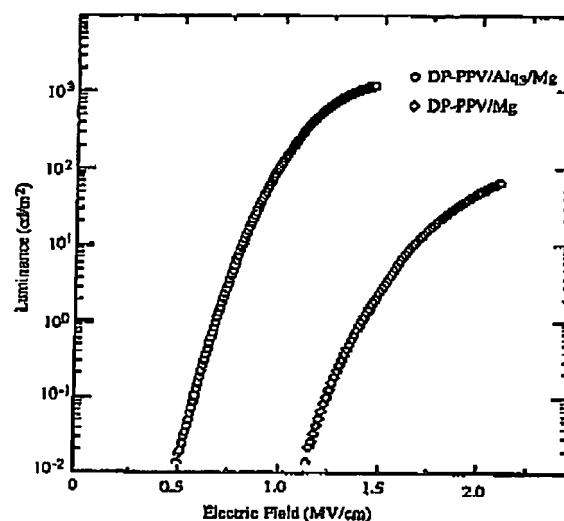


Figure 11. Luminance versus average applied electric field for single layer (ITO/DP-PPV/Mg) and bilayer (ITO/DP-PPV/Alq₃/Mg) devices.

compared with the single layer without Alq₃. This is attributed to the improvement in electron injection and the improved balance of holes and electrons.⁴³

Summary

High-quality DP-PPV films of 400 Å to 10 μm can be readily prepared by the chlorine precursor route. Absorption and emission measurements of samples converted at different temperatures shows the existence of a well-defined thermodynamic barrier at 150–170 °C in the conversion process. Below 150 °C, the polymer still exhibits the precursor properties, while above 170 °C, the polymer is fully converted to DP-PPV. Increasing the conversion temperature or converting for a longer period of time only leads to a morphology change that does not significantly affect the luminescence properties of the polymer. However, the thermal conversion is accompanied by the formation of carbonyl moieties within the polymer whose quenching effect on the PL becomes critical when the conversion temperature is as high as 300 °C. The photoconductivity of DP-PPV is 2–3 orders of magnitude less than PPV. A significant improvement in EL efficiency and a reduction in the turn-on voltage was observed for an ITO/DP-PPV/Mg device when a thin layer of Alq₃ was deposited between the cathode, Mg, and DP-PPV.

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References and Notes

- (1) Burroughes, J. H.; Bradley, D. D. C.; Brown, A. R.; Marks, R. N.; Mackay, K.; Friend, R. H.; Burn, P. L.; Holmes, A. B. *Nature* 1990, 347, 539.

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- (2) Hsieh, B. R. In *Polymeric Materials Encyclopedia*; Salamone, J. C., Ed.; CRC Press, Inc.: Boca Raton, FL, 1996; Vol. 9, p 6537 (see also references therein).
- (3) Schott, M. In *Organic Conductors: Fundamentals and Applications*; Farges, J.-P., Ed.; Marcel Dekker: New York, 1994; Vol. 12, pp 539-646.
- (4) Horowitz, G. *Adv. Mater.* 1990, 2, 287-292.
- (5) (a) Saricic, N. S.; Braun, D.; Zhang, C.; Srdanov, V. I.; Heeger, A. J.; Stucky, G.; Wudl, F. *Appl. Phys. Lett.* 1993, 62, 585. (b) Saricic, N. S.; Smilowitz, L.; Heeger, A. J.; Wudl, R. *Synth. Met.* 1993, 59, 333.
- (6) Antoniadis, H.; Hsieh, B. R.; Abkowitz, M. A.; Jenekhe, S. A.; Stolka, M. *Synth. Met.* 1994, 62, 285-271.
- (7) (a) Hsieh, B. R.; Antoniadis, H.; Abkowitz, M. A.; Stolka, M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* 1992, 33(2), 414-415. (b) Antoniadis, H.; Hsieh, B. R.; Abkowitz, M. A.; Jenekhe, S. A.; Stolka, M. *Mol. Cryst. Liq. Cryst.* 1994, 256, 381. (c) Antoniadis, H.; Abkowitz, M. A.; Hsieh, B. R. *Appl. Phys. Lett.* 1994, 65, 2030. (d) Antoniadis, H.; Abkowitz, M. A.; Hsieh, B. R.; Jenekhe, S. A.; Stolka, M. *Mater. Res. Soc. Symp. Proc.* 1994, 328, 377. (e) Abkowitz, M. A.; Antoniadis, H.; Facci, J. S.; Hsieh, B. R.; Stolka, M. *Synth. Met.* 1994, 67, 187-191.
- (8) (a) Koezuka, K.; Tsumura, A.; Fuchigami, H.; Kuramoto, K. *Appl. Phys. Lett.* 1993, 62, 1794-1796. (b) Fuchigami, H.; Tsumura, A.; Koezuka, H. *Appl. Phys. Lett.* 1993, 63, 1372-1374.
- (9) Garnier, F.; Hajlaoui, R.; Yassar, A.; Srivastava, P. *Science* 1994, 265, 1684.
- (10) Dodabalapur, A.; Torsi, L.; Katz, H. E., *Science* 1995, 268, 270.
- (11) Yang, Y.; Heeger, A. J. *Nature* 1994, 372, 344.
- (12) (a) Bradley, D. D. C. *Adv. Mater.* 1994, 4, 756. (b) Baigent, D. R.; Greenham, N. C.; Gruner, J.; Marks, R. N.; Friend, R. H.; Moratti, S. C.; Holmes, A. B., *Synth. Met.* 1994, 67, 3. (c) Cacialli, F.; Friend, R. H.; Moratti, S. C.; Holmes, A. B. *Synth. Met.* 1994, 67, 157.
- (13) Pei, Q.; Yu, G.; Zhang, C.; Yang, Y.; Heeger, A. J. *Science* 1995, 269, 1086.
- (14) MacDiarmid, A. D.; Wang, H. L.; Huang, F.; Avlyanov, J. K.; Wang, P. C.; Swager, T. M.; Huang, Z.; Epstein, A. J.; Wang, Y.; Gebler, D. D.; Shaahidhar, R.; Calvert, J. M.; Crawford, R. J.; Vargo, T. G.; Whitesides, G. M.; Hsieh, B. R. *MRS Proc.* 1996.
- (15) Burn, P. L.; Kraft, A.; Baigent, D. R.; Bradley, D. D. C.; Brown, A. R.; Friend, R. H.; Gymer, R. W.; Holmes, A. B.; Jackson, R. W. *J. Am. Chem. Soc.* 1993, 115, 10117-10124.
- (16) Hsieh, B. R. *Polym. Mater. Sci. Eng.* 1992, 67, 252.
- (17) Hsieh, B. R.; et al. U.S. Patent Application.
- (18) Hsieh, B. R.; Antoniadis, H.; Bland, D. C.; Feld, W. A. *Adv. Mater.* 1995, 7, 36-39.
- (19) Hsieh, B. R.; Razafitrimo, H.; Gao, Y.; Feld, W. A. *Polym. Mater. Sci. Eng.* 1995, 73, 567-568.
- (20) Hsieh, B. R.; Razafitrimo, H.; Gao, Y.; Feld, W. A. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* 1995, 36(2), 85-86.
- (21) Son, S.; Dodabalapur, A.; Lovinger, A. J.; Galvin, M. E. *Science* 1995, 269, 376.
- (22) Fou, A. C.; Onitsuka, O.; Ferreira, M.; Rubner, M. F.; Hsieh, B. R. *J. Appl. Phys.*, submitted for publication.
- (23) Onitsuka, O.; Fou, A. C.; Ferreira, M.; Hsieh, B. R.; Rubner, M. F.; Submitted for publication to *Science*.
- (24) Hsieh, B. R.; et al. *Proc. IS&T*, in press.
- (25) (a) Reinhardt, B. A. Carboethoxy-Substituted Polyphenylenes M.S. Thesis, WSU, 1971. (b) Harris, W. H.; Reinhardt, B. A. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* 1974, 15(1), 691-695.
- (26) Gaiherger, M.; Bässler, H. *Phys. Rev. B* 1991, 44, 8843.
- (27) Bradley, D. D. C.; Friend, R. H. *Synth. Met.* 1987, 17, 651.
- (28) Papadimitrakopoulos, F.; Yan, M.; Rothberg, L. J.; Katz, H. E.; Chandross, E. A.; Galvin, M. E. *Mol. Cryst. Liq. Cryst.* 1994, 256, 683.
- (29) Papadimitrakopoulos, F.; Konstantidis, K.; Miller, T. M.; Opiela, R.; Chandross, E. A.; Galvin, M. E. *Chem. Mater.* 1994, 6, 1563.
- (30) Hsieh, B. R.; Feld, W. A. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* 1993, 34(2), 410.
- (31) Cumpston, B. H.; Jensen, K. F. *Synth. Met.* 1995, 73, 195.
- (32) Sutherland, D. G. J.; Carlisle, J. A.; Elliker, P.; Fox, G.; Hagler, T. W.; Jimenez, I.; Lee, H. W. H.; Pakbaz, K.; Terminello, L. J.; Williams, S. C.; Himpel, F. J.; Shuh, D. K.; Tong, W. M.; Callcot, T. A.; Ederer, D. L. *Appl. Phys. Lett.* 1996.
- (33) Samuel, I. D. W.; Crystall, B.; Rumbles, G.; Burns, P. L.; Holmes, A. B.; Friend, R. H. *Synth. Met.* 1993, 54, 281.
- (34) Yan, M.; Rothberg, L.; Papadimitrakopoulos, F.; Galvin, M. E.; Miller, T. M. *Phys. Rev. Lett.* 1994, 73, 744.
- (35) Jenekhe, S. A.; Osaheni, J. A. *Science* 1994, 265, 765.
- (36) Gilbert, A.; Baggot, J. *Essentials of molecular photochemistry*; CRC Press: Boca Raton, FL, 1991.
- (37) Pichler, K.; Halliday, D. A.; Bradley, D. D. C.; Burns, P. L.; Friend, R. H.; Holmes, A. B. *J. Phys. Condens. Matter* 1993, 5, 7155.
- (38) Antoniadis, H.; Rothberg, L. J.; Papadimitrakopoulos, F.; Yan, M.; Galvin, M. E.; Abkowitz, M. A. *Phys. Rev. B* 1994, 50, 14911.
- (39) Parker, I. D. *J. Appl. Phys.* 1994, 75, 1656.
- (40) Zhang, C.; Heger, S.; Pakbaz, K.; Wudl, F.; Heeger, A. J. *J. Electron. Mater.* 1993, 22, 413.
- (41) Braun, D.; Heeger, A. J. *Appl. Phys. Lett.* 1991, 58, 1982.
- (42) Wu, C. C.; Chun, J. K. M.; Burrows, P. E.; Sturm, J. C.; Thompson, M. E.; Forrest, S. R.; Register, R. A. *Appl. Phys. Lett.* 1995, 66, 553.
- (43) Littman, J.; Martic, P. *J. Appl. Phys.* 1992, 72, 1957.

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